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TECHNOLOGY STATUS OF HYDROGEN ROAD VEHICLES

by

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1.0 Introduction

This report was commissioned under the Hydrogen Implementing Agreement of the International Energy Agency (IEA), and examines the state of the art in the evolving field of hydrogen-fueled vehicles for road transport. The first phase surveys and analyzes developments since 1989, when a comprehensive review was last published (DeLuchi 1989). The report emphasizes the following:

- Problems, especially backfiring, with internal combustion engines (ICEs)
- Operational safety
- Hydrogen handling and on-board storage
- Ongoing demonstration projects.

Hydrogen vehicles are receiving much attention, especially at the research and development level. However, there has been a steady move during the past 5 years toward integral demonstrations of operable vehicles intended for public roads. Because they emit few, or no greenhouse gases, hydrogen vehicles are beginning to be taken seriously as a promising solution to the problems of urban air quality.

Most information sources for this report are published documents. Some were supplied by IEA and European Community officials, but most were accessed from the document retrieval systems in common scientific use. Several hundred documents were scanned for interest; about 150 were studied for relevance to this report. Most had some bearing on the way the report is presented, but only the 50 actually quoted or referred to in the text are listed in the References section. Much work of direct relevance is undoubtedly missing, either because it is too recent or too proprietary. In a fast-moving field of some industrial importance, the best results are kept under wraps until the time is ripe for exploitation. And some relevant published work may have been overlooked.

The starting point for this study is the comprehensive work of DeLuchi (1989). It is rich with the input of 165 documents consulted, and should be read in conjunction with this report. In particular it makes a life-cycle cost comparison among the various technologies, and concluded that even 6 years ago the economics of some hydrogen vehicles was already competitive.

Since the time the first draft of this report was prepared (mid-1996), the 11th World Hydrogen Energy Conference took place in Stuttgart, Germany. This biennial conference can be regarded as a valid updating of the state of the art; therefore, the 1996 results are included in this current version. Those of interest to hydrogen vehicles are discussed throughout this report, with the most detail included in Appendix 4.

A summary of DeLuchi 1989 is also included. For convenience, this is also presented in Appendix 4. As a consequence of this updating, we also became aware of a valuable report, not yet available in the public literature, concerning a comprehensive safety investigation on hydrogen (EQHHPP Nov. 1993). Awaiting its publication, we can only include a brief summary in Appendix 1 on safety questions.

2.0 Hydrogen Production and Distribution to Urban Users

2.1 Hydrogen Production and Bulk Transport

Hydrogen as a fuel (or more correctly as an energy vector) for any application is inseparable from its basic rationale: recourse to *clean and renewable energy* (*clearen*). The interdependence of hydrogen and *clearen* is so strong that one can hardly become widespread without the other.

Clearens are all sun-derived on a short cycle, and include photovoltaics, wind, hydropower, and energy crops on time scales that range from instantaneous to a few years. All originate in settings that are somewhat remote; without a suitable vector, they may never make much impact, especially on urban transport. Hydrogen is such a vector, and in its pure form does not disturb the environmental merits of *clearens*. Whether it should be used alone or in combination with a carrier (e.g., methanol is a liquid carrier similar to other oil products; reduced iron is a carrier similar to ore) is still an open question. In fact, there may be several competitive approaches to what may become a major shipping industry that will bring *clearens* from remote to industrialized areas.

This report does not define the technological status of these approaches to bulk hydrogen production and transport. For present purposes, large quantities are not necessary to fuel a limited number of prototype and small-fleet demonstrations of hydrogen vehicles. Even when the niche markets imposed by regional legislation become reality, *clearen*-derived hydrogen is not a must; any local supply of hydrogen such as refinery off gases or even electrolyzers powered by local electricity will suffice. The point is, there is nothing wrong with decoupling early hydrogen vehicles from *clearen*-derived hydrogen; any hydrogen will do. Storage batteries are accepted as the motive power for zero-emission vehicles (ZEVs) and they, like home/local electrolyzers, simply shift the fossil fuel pollution, albeit much reduced, from local to power plant settings. In some vehicle applications such as fuel cells (FCs), the impurity levels in the hydrogen could be important. However, water electrolysis (which seems to be the front runner in *clearen*-derived hydrogen) is very pure (>99.999%).

There is increased emphasis in the 11th WHEC (see Appendix 4) on hydrogen derived from hydrocarbon sources, especially by reforming of methane or methanol; this trend will be discussed throughout the report. Moore and Raman (1996) and Ogden (1996) examine various options of putting hydrogen into the vehicles in cities.

2.2 Urban Distribution

Hydrogen distribution is, especially in an urban setting, less straightforward than that of almost any other gas or liquid fuel. Even if town gas (before the arrival of natural gas) contained considerably more hydrogen, it still could not be compared to pure hydrogen from handling and safety points of view. In fact, hydrogen's interface with the public is one of its main hurdles. This interface is dominated by safety concerns, both real and perceived.

The real safety questions have received considerable attention, and will always be integral to vehicle design and operation. They are fundamental to any hydrogen application (especially urban transport); the important results are summarized in Appendix 1.

The safety of hydrogen is so different from that of conventional fuels that simple comparisons can be misleading. The precise application is critical. In general, if hydrogen is properly handled, its safety potential exceeds conventional hydrocarbon fuels; improperly handled (especially if it leaks in confined spaces), it can be more explosive. Designing and operating hydrogen vehicles to guarantee adequate safety are matters for engineers and regulatory authorities. Hydrogen should not affect driving or life styles, unless vehicles are parked in garages or other confined spaces that do not have proper and guaranteed ventilation.

The automotive industry has usually listened to the experts about safety issues, especially since the 1960s when safety moved to the forefront of most designs. But that is not true of all industries: the Challenger accident is a reminder of what happens when other pressures overwhelm safety. The measures available to keep safety at the forefront are discussed in Appendix 1.

The perceived safety questions can be more intractable, particularly in a startup phase of hydrogen vehicles.

Memories of the Hindenburg disaster can mislead even the technically informed. False analogies with the hydrogen bomb can upset the larger public. Only a steady flow of correct, unbiased information, backed by concrete demonstrations, can slowly break down the barriers of false perceptions.

Regarding the logistics of distributing hydrogen to urban users, it is always produced as a gas (GH_2) and, before the space age, was distributed as compressed GH_2, sometimes in pipelines or in large cylinders to individual consumers. No particular problems were associated with these deliveries, regulatory authorities in most industrial countries have issued the regulations, and no major hydrogen-specific accidents have been reported.

Fueling rockets for spacecraft requires hydrogen at maximum density: liquid hydrogen (LH_2) at -253°C and 2 bar. Now a mature technology (at least for substantial quantities of LH_2), it is opening a promising option for bulk hydrogen shipment and even for on-board storage for hydrogen vehicles (see Chapter 3).

The liquefaction energy of LH_2 (0.95 kWh/liter or about one-third of its lower calorific value) is often cited as a major drawback. Work is proceeding on minimizing this energy, but Niermann and Roth (1993) have shown that a substantial improvement in the process efficiency is hardly to be expected. The energy is undeniably high, but cryogenic hydrogen can be useful, if not vital, for good performance of some prime movers. This matter is discussed in more detail in Chapter 4.

Bottled GH_2 continues to be supplied to small-scale users, but major clients are supplied by large (some 40,000 liters) LH_2 tankers with super-insulation and provision for boil-off (Ewald 1990). Such a tanker could supply about 300 ICE or 950 FC vehicles with enough LH_2 to travel approximately 350 km.

According to Hynek and Moore (1995), the major shipper in the United States makes about 50 bulk shipments per day in LH_2 highway tankers to industries nationwide, with no incident of consequence. Moore and Raman (1996) confirm that this merchant hydrogen--as used in the chemicals, metals, glass, and electronic industries--is shipped as LH_2 (U.S. capability 80,000 tonne/yr, in 20,000 trailer loads per year); by comparison, the space industry consumes only a tiny fraction.

The same paper examines four basic ways of getting hydrogen to the vehicle: large-scale LH_2 by tanker from a remote facility, large-scale GH_2 by pipeline from a regional facility, small-scale GH_2 at a fueling station, and a home electrolyzer. The first three are based on steam methane (or heavy oil) reforming to hydrogen, and the option of converting to methanol at the fueling station is included. The main conclusion is that the wholesale price range at the fueling station ranges from \$2.30 to 3.30 per kg hydrogen, except for home electrolysis, which would be about double.

Ogden (1996) examines similar options but concludes that large-scale hydrogen shipping is probably done most economically by GH_2 pipeline from a remote or regional facility for steam methane reforming or for excess refinery hydrogen. An indicated strategy is to start vehicle fleets with trucked LH_2 or with on-site reforming or electrolysis; go for pipeline GH_2 supply when tens of thousands of vehicles become involved; build a dedicated facility after half a million vehicles are involved. As the price of natural gas becomes non-competitive, switch to renewable energies.

Specht et al. (1996) examine the energetic and cost factors of bringing LH_2 and methanol (using atmospheric CO_2 for the carbon molecule) from remote hydropower facilities to Europe, and compares both to crude oil-gasoline. The overall efficiency of the crude oil-gasoline-vehicle system is about 19%, compared to about 9% for methanol and slightly less for LH_2. Untaxed, the environmentally friendly fuels cost about the same, and each is about 25% more expensive than gasoline.

3.0 On-Board Storage and Refilling

The design and layout of conventional vehicles never gave much priority to fuel storage. The tank was always comparatively simple, operated at ambient conditions, and contained gasoline or diesel fuel for a range of about 500 km.

On-board storage of hydrogen is quite a different matter. The tank is not simple, and conditions are never ambient. Some combination of high pressure, cryogenic temperature, and thermal processing is necessary, depending on the storage form. Refueling such tanks is correspondingly complicated.

Ewald (1996) states that a successful hydrogen vehicle must be tailored to the storage system. Three fundamentally different ways have been developed for on-board hydrogen storage, and even though much research and development is still ongoing, working versions are currently available:

- Compressed GH_2 in high-pressure reinforced vessels, ambient temperature
- Metal hydrides (MH) in medium-pressure vessels, ambient temperature when passive, heat input for active flow
- Liquid LH_2 in low-pressure vessels, cryogenic temperatures of -253°C.

Other hydrogen storage methods have been attempted, such as iron pre-reduced by H_2 released again in a steam-iron reaction, or as a hydrogen-rich reformable liquid under ambient conditions. These efforts are at least partially related to a more general problem of stationary bulk storage and shipping of hydrogen, whereas a methylcyclohexane/toluene cycle is foreseen for seasonal storage of hydropower energy (Schucan and Taube 1986). Methanol can perform a similar function for biomass (Frolov et al. 1994). These and other efforts will no doubt contribute to the separate question of optimized bulk stationary storage of hydrogen. Attempts to use methanol on-board are meeting with some success; in fact, Daimler-Benz has operated an A-class vehicle on a reformed methanol FC. Due to the limited number of successes to date of these storage methods, they will not be considered further in this report, but future developments may warrant their inclusion in later studies. In fact, several papers presented at the 11th WHEC illustrated continued interest in these topics:

- Ekdunge and Råberg (1996) consider on-board reforming of methanol
- Ewald (1996) prefers only direct use of methanol, Cleghorn et al. (1996) quote record performance of direct methanol fuel cells, and Schmidt and Stimming (1996) mention the latter possibility
- Pizak et al. (1996) conclude that on-board steam-iron production of hydrogen could be practicable, but is best started in heavy transportation systems such as locomotives.

3.1 Compressed Gas

For many years GH_2 was supplied to various industries in steel cylinders of reduced diameter and pressures as high as 300 bar. These cylinders had poor energy densities on a mass and volume basis, but the quantities involved were usually small, and stationary storage the norm. The advent of fiber-wrapped aluminum vessels, and then composite material in the pressure vessel, has alleviated the problem, and prototype pressures are reaching higher than 600 bar. Energy density has had a strong effect on a mass basis, but only a modest effect on a volume basis.

Substituting the steel pressure vessel with much lighter material has the major effect and is compounded by the pressure increase. These advanced vessels seem to have received regulatory approval in several countries, since there are references to their use on a prototype basis. But actual H_2 vehicles (presented in Table 1) do not exceed 300 bar, and little information is available for the next generation, presented in Table 2.

As Hynek (1995) pointed out, lowering the temperature to that of liquid nitrogen (-195°C) at 250 bar gives GH_2 almost the same density as LH_2.

During the past 5 years, a carbon sorption technique in the pressure vessel has allowed both the mass and volume densities to be almost doubled, depending on the bulk hydrogen pressure. Unfortunately, the effect seems to be most marked at pressures lower than 70 bar (Hynek et al. 1994).

Zeolites (aluminosilicates) may be a promising way of allowing more hydrogen to be held within a given volume. Querubin et al. (1994) states that zeolites, whose bulk density is about 10 times that of activated carbon, are expected to be about four times better for hydrogen storage on a unit volume basis. A similar line is represented by micro-encapsulation of hydrogen in glass. Duret and Saudin (1992) in France and Akunets et al. (1992) in Russia have investigated this. Both achieved improved weight density.

Griesinger et al. (1996) treat ongoing basic work on zeolites, and mention the possibility of new synthetic zeolites with improved storage capability.

No figures are available that predict the results of these various lines of research. The research will continue, however, because, at high pressures and with improved sorption techniques, GH_2 systems (at liquid nitrogen temperatures) may approach those for LH_2 on a mass and volume density basis.

Ewald (1996) states, however, that there is little point in using pressures higher than 300 bar because the supply infrastructure becomes quite difficult, and the filling factor decreases because of non-ideal gas behavior.

Compared to LH_2 or MH, refilling simple GH_2 vehicles is rather straightforward if a bulk storage vessel with the necessary pressure difference is available. Open-air, well-ventilated stations are required, and the level of personnel expertise is not too high. A vehicle can probably be refilled in several minutes, but little information is available.

3.2 Metal Hydrides

Metal hydrides are formed when hydrogen is added under modest pressure to suitable alloys in an exothermic reaction that seems simple to control:

$$\text{e.g.}\quad FeTi + H_2 \div FeTiH_2 + \text{heat} + 25\%\ \text{volume increase}$$

The GH_2 is recovered by adding heat, in this case at a modest temperature of 70°C, which could easily be supplied by the exhaust heat or cooling water of the prime mover. Startup requires supplementary measures.

The metals of interest (the most common after Fe, Ti being Mg, Ni, Mn, etc.), although not as rare as some catalysts they resemble, can probably experience decomposition and pulverization over a limited life, and rapid loss of their storage capabilities. This may be the only way of storing hydrogen so it cannot escape in bulk during an accident or operational leaks and vents. Heat must be deliberately added to release the hydrogen, and the system never has more free hydrogen than required for immediate needs.

So this great advantage decreases as the other storage systems reach excellent standards of containment. Still, it explains the favor bestowed on it for early, startup research and development and for some prototypes. It is, however, almost the only advantage. Its major drawback is poor energy density on a weight basis, which is about half that of 300 bar GH_2. Even though on a volume basis it can outperform GH_2 (though not LH_2) the weight penalty so far is severe in mobile applications. However, interest remains high, and much work is underway to unearth the metal combinations that could reduce the weight penalty to manageable proportions and maintain structural integrity under repeated cycling over many years. Related fields of powder metallurgy and catalysts may provide unexpected inputs.

Refilling procedures are more complicated than for GH_2, because of the thermal management required for the exothermic reaction. However, the refill times seem to be acceptable, especially if less than 100% full is requested, but this of course reflects itself directly into a reduced range.

3.3 Liquid Hydrogen

This storage method is adopted in the space industry because it is a clear winner on the basis of energy density per unit weight.

Supplies of bulk hydrogen for most applications are presently made by LH_2 tanker (except for isolated cases in which a GH_2 supply is located close to the application), so on-board LH_2 for road vehicles has a logistical advantage. The preferred method of shipping merchant hydrogen is as LH_2 (Moore and Raman 1996). The major drawbacks of LH_2 are the energy of liquefaction (about one-third of the lower calorific value), and the need to maintain very low temperatures (-253°C at 2 bar).

But the following should be kept in mind:

- Some prime movers give better performance on cryogenic than on ambient hydrogen; this comes about because in the ICE the combustion must be cooled to avoid backfire, knock, and excess NO_x; cold H_2 displaces less air than ambient H_2 resulting in increased power.
- Most industrial nations have climates that need air conditioning for at least several months per year. McKenzie (1994) states that about 50% of all new vehicles sold worldwide have air conditioning, and refrigerated goods transport is constantly on the rise; while CFCs with their disproportionate contribution to the greenhouse effect are being phased out, their replacement HFCs still emit about half the CFC effect. Amann (1992) claims that air conditioners in the United States will contribute more CO_2-equivalence than the tailpipe emissions until about 2015. Using LH_2 as a refrigerant as well as a fuel avoids all that, as amply demonstrated by the Musashi-9 van (see Table 1, item 15).
- Scott et al. (1996) point out that the 10% thermomechanical energy present in LH_2 total energy, because of the processing down to cryogenic temperatures, could be largely recovered by, for example, using the LH_2 as heat sink in a cryonic heat engine.

The cryogenic temperature drawback needs super-insulation to keep the boil-off losses within acceptable limits (below 2%/day for vehicles). This will always add to the costs, and aggravates the already low volumetric density. Boil-off gases can sometimes be productively used, which in turn would eliminate the potential safety problem of vented hydrogen. But there is no escaping the boil-off problem, especially for parked vehicles, although Hynek and Moore (1995) tend to minimize it. Michel et al. (1996) show how LH_2 now need suffer no boiloff for several days.

LH_2 refueling for vehicles has received considerable attention during the past decade, especially in Germany. Industrial systems are being used for the relevant projects described in the next chapter. One thing is already clear: LH_2 refueling must be almost fully automatic, with little human intervention except at the beginning and end. Expert supervision will be required, although Hynek and Moore (1995) again tend to minimize the matter. However, in this case it can become an acceptably fast procedure (Tachtler and Szyszka 1994).

Nothing in the literature deals with the question of initial filling, i.e., with the vehicle tank at ambient temperature, presumably because ad-hoc measures were taken. However, vehicles that run out of LH_2 will be almost as common in the future as vehicles fueled today with conventional fuels. Driving to the service station will be a problem, and the filling procedure will be more complicated and time-consuming. This disadvantage seems particularly applicable to LH_2. The hybrid vehicles described in section 4.3 can partially solve this problem.

Wetzel (1996) gives a comprehensive summary of the special facility operating in Germany since 1991, dedicated to the improvement of LH_2 handling at refueling stations. All operations in the three main refueling phases (connect--cool down, filling proper, depressurize--disconnect) are automatic, except the relatively simple ones of connect and disconnect. Total refueling times are now down to 8.6 or 5.2 minutes depending on the coupling used, and LH_2 releases (which are largely recuperable) are correspondingly down to 14.2 or 8.0 liters, respectively. These improvements are valid for the BMW test car (Item 1 Table 1) which was frequently refueled at the facility. Hettinger et al. (1996) describe more qualitatively a mobile filling station for refueling cars and buses with LH_2.

Yamane and Furuhama (1996) is a parameter study concerning on-board hydrogen storage, showing the effect of total weight of fuel and fuel tank on the main parameters that affect car performance; it concludes by stating that only LH_2 offers the accustomed performance.

4.0 Vehicle Power Units and Drives

When conventional vehicles were introduced at the end of the last century, several approaches to the fundamental choices of engine and drive were taken, but the winner--the ICE with geared drive--quickly emerged and has remained dominant for most of this century. This is not likely to happen with hydrogen vehicles in the foreseeable future.

As discussed, the choice of fuel storage has a strong influence on system layout, and can directly affect the choice of prime mover. For example, only LH_2 today seems capable of giving a hydrogen ICE a range comparable to conventional fuels, at least for cars with limited space; on the other hand, an FC with its much higher efficiency confers greater flexibility on the choice of fuel storage.

More fundamentally, enough progress has been made during the past 5 years to reinforce the conviction, already tentative in DeLuchi's 1989 report, that FCs are a more natural partner for hydrogen in whatever form, and possess the potential of lower life-cycle costs than the ICE. It is still too early for definite conclusions, and indeed there is good reason to think that the ICE and a successful FC can coexist for many decades.

The proliferation underway in prime mover research, development, and demonstration can be conveniently grouped in three broad categories:

- The ICE, usually reciprocating but including the rotary version
- FCs, especially the two types most indicated today for mobile applications
- Hybrids, which re-dimension the prime mover (ICE or FC) size down to average running loads, and cover transients with energy-storage devices such as batteries, capacitors, or flywheels.

A fourth category could include more speculative concepts; e.g., the external combustion engine--the Stirling engine is being re-examined because of its adaptability to H_2. They are not included because of lack of information.

Lund (1996) illustrates an innovative type of hydrogen vehicle that is emerging from the classic electric vehicle. Instead of traditional lead-acid batteries, Toyota and Panasonic envision upgrading their innovative Ni-metal hydride batteries to vehicle size, thereby improving energy density and reducing vehicle weight.

4.1 Internal Combustion Engines

The ICE is highly optimized for conventional fuels, but is an awkward partner for hydrogen. This is surprising at first glance, perhaps because of hydrogen's excellent combustion characteristics. The problem is that the conventional reciprocating ICE prefers more docile fuels, and has difficulty accommodating hydrogen. Appendix 2 explains this in simple terms, but it should be regarded only as a primer that provides some fundamentals and available operating experience to define the status quo.

In essence, it can be affirmed that:

- Ambient H_2 displaces considerable air, and power loss is inevitable. For example, at stoichiometry a hydrogen/air mixture has only 85% of the gasoline/air mixture energy.
- Allowing hydrogen to be aspirated with air on the intake stroke leads to uncontrollable backfiring and further power loss (as much as 25%) because of the inevitable hot spots from the overlapping exhaust stroke, and even (Kondo et al., 1996) because of the residual voltage in the spark plug cable.
- Injecting hydrogen at the start of the compression stroke prevents backfiring and is not difficult, but pre-ignition and power loss can still occur.
- Injecting hydrogen near top dead center (TDC) prevents backfiring, pre-ignition, and power loss, but needs pressures higher than 100 bar, very finely tuned starts and durations of injection, and correspondingly precise ignition--all to millisecond levels.
- Cryogenic hydrogen is helpful in all cases simply because it cools the mixture without power loss that other coolants (water, inert gas, etc.) entail, but cryogenic pumps and injectors have their own problems, especially cavitation and lubrication.

The familiarity of the conventional reciprocating ICE makes it a leading contender, and barring major breakthroughs in other fields, it will advance steadily in its difficult adaptation to hydrogen. Emissions are very low compared to conventional fuels, although NO_x can be somewhat higher near stoichiometry, and trace quantities of HC, CO, and CO_2 arise from lubricating oil.

Takano et al. (1992) claim that the rotary ICE can minimize uncontrolled combustion of hydrogen simply because the different strokes occur in different locations with high surface/volume ratios, giving adequate cooling possibilities to prevent backfiring or pre-ignition. The argument is persuasive and a demonstration car is actually running, but the problems of rotary engines are not solved by a shift to hydrogen. This Mazda single-rotor engine seems also the one investigated by Brown and Green (1996), where low-pressure hydrogen injection into the inlet manifold in fact caused no backfiring or uncontrolled combustion over a wide range of load and air-fuel ratio; but the maximum power was much reduced, and the efficiency was lower, compared to gasoline.

Any mechanical engine with hydrogen/air combustion will produce CO, CO_2, and HC in trace quantities from the lubricating oil, and NO_x from the air. These products at the tailpipe may exclude ICEs fueled by hydrogen from the ZEV designation now being discussed in the United States. As things stand, U.S. suppliers are adopting a cautious approach and seem more interested in offering electric vehicles (storage batteries or FCs) than hydrogen ICEs to meet ZEV legislation. If this is the only viable approach, the hydrogen ICE will be excluded from the major U.S. markets for the important startup phase of ZEVs.

McKenzie (1994) predicts that as many as 1.7 million cars and light trucks will be sold as ZEVs by the year 2003. In his book, and indeed in most U.S. publications, these are all seen as electric vehicles (storage batteries or FCs); little or no consideration is given to ICEs.

The ICE's difficult partnership with hydrogen is aggravated if it must provide the marvelous flexibility it enjoys with gasoline or diesel fuels over a wide range of powers and speeds. An elegant solution to the problem would be to reduce the ICE size to that required to meet the average load only of the vehicle at constant running speed, leaving the transient acceleration (and deceleration) variables to an energy storage device. This is the promising hybrid version described in section 4.3.

The 11th WHEC shows increasing interest in FCs for transportation applications, but the ICE proponents are still forcefully present. Provenzano et al. (1996) report on successful ICE operation of three hydrogen trucks, as do Knorr et al. (1996) for a full-size city bus; Peschka (1996) favors a combination of early and late injection of LH_2 to reach comparable performance as gasoline, but with very low NO_x; he finds the FC unattractive on a power/weight basis. Some major European car manufacturers such as Volvo (Ekdunge and Råberg 1996) and Mercedes (Dönitz 1996; Friedrich and Noreikat 1996) report favorably on FCs; Friedrich and Noreikat have been major developers of the hydrogen ICE, as summarized by Digeser et al. (1996).

4.2 Fuel Cells

The FC, like LH_2, was brought into widespread use in the space industry, and some versions have made enormous strides during the past 5-10 years. Appendix 3 introduces FCs, enumerates the ones receiving most attention in a general sense, and focuses on the two types of most interest for vehicles:

- The proton exchange membrane (PEM) FC, which operates at low temperature (~80°C), has reasonable efficiency (~55 %), starts up in seconds, has good dynamic response and a promising lifetime (~same as vehicle); it is emerging as the favorite FC for vehicles (see in Tables 1 and 2).
- The alkaline fuel cell (AFC), which operates at about the same temperature as the PEM FC but with a liquid electrolyte and a lower power density.

The main disadvantage of the PEM is its need for platinum (Pt) catalyst at the electrodes, at least an order of magnitude greater than the Pt content of today's catalytic converters for ICE mobile application. However, the need for Pt in the PEM FC is decreasing. Another disadvantage is the cost of the solid polymer membrane, which comes in several trademarked versions. But as Appleby (1992) points out, the basic polymer material is quite cheap.

Dönitz (1996) states that in 1990 these two cost items were roughly equal per unit power output (320 DM/kW for Pt loading of electrodes, 250 DM/kW for Nafion membrane). He claims that the Pt loading has sunk to only 55 DM/kW in 1996, and can reach 6 DM/kW over the long run, making it no bar to commercialization. However, only volume production and/or the development of new polymers can bring down the cost of the membrane.

Rusanov (1996) states that a Russian solid polymer membrane costs several times less than Nafion.

Scherer et al. (1996) describe initial characterization tests on novel proton conducting membranes.

Bevers et al. (1996) describe potential improvements in mass production of reproducible PEM electrodes.

The AFC has different catalysts, and is intolerant to CO and CO_2. This may help explain its lack of favor: only two projects--now terminated--figure on Table 1, and none on Table 2.

Although the PEM FC comes closest to the ICE on a specific power (kW/kg) basis, the 11th WHEC gives some conflicting figures:

- Peschka (1996) claims that the hydrogen ICE will continue to enjoy the order-of-magnitude advantage it has over H_2-air FC: 1 kW/kg vs. 0.1 today, increasing to 1.8 versus 0.2
- Ekdunge and Råberg (1996) give an ICE and an FC option for a five-passenger Volvo car: the 93-kW ICE weighs 1,450 kg; a 75-kW FC would weigh 1820 kg plus 123 kg of buffer batteries for the same total peak capability of 93 kW
- Friedrich and Noreikat (1996) quote 20 kg/kW for the Mercedes Benz PEM FC of Item 9 Table 1, and claims that this can be improved by a factor 4 to 5; another author from the same company, Dönitz (1996)

sees a figure of approximately <1 kg/kW within a decade

- Mantegazza and Maggiore (1996) quote 25 kg/kW for the PEM FC of Item 6 Table 1, which improved to 10 kg/kW for that of Item 9 Table 2, and is expected to reach 5 kg/kW by 1999.

FCs may remain more expensive for the foreseeable future than hydrogen ICEs on an equal power basis, but DeLuchi already established (1989) that the life-cycle costs of H_2 vehicles with PEM FC can be inferior to ones with hydrogen ICE, and the situation since then has evolved more in favor of the PEM FC.

The major benefits of the PEM, and indeed of any FC, are environmental (no exhaust emissions except water) and energy efficiency at all loads (double or more that of the ICE over a driving cycle). Together these huge advantages have great implications for future urban and inter-urban transport, rail, and waterway as well as road. If progress of the past few years continues--and there is no apparent reason why it should not--the long reign of the ICE may come to an end. But the ICE is so entrenched in the economic life of the industrial world that any decline will be slow.

Ekdunge and Råberg (1996) estimate that near-term FCs, because of their low specific power and high response time for on-board reformers (where used), can have fuel consumptions as high as 65% (without reformer) and 91% (with reformer) of an ICE, but confirms future values of 40% and 53% respectively.

Hydrogen and FCs are natural partners. Indeed, FCs run almost exclusively on hydrogen (although a hydrogen-rich fuel such as methanol when reformed to H_2 and cleaned of CO could be used, and would ease the transition to H_2) and air (oxygen would give higher efficiency). The electrochemical reactions are fast enough, even with air, to give good driving flexibility, without being hard to control as in the case of H_2/air combustion. Barbir (1996) gives the results of various control strategies on FC performance and shows that adopting a variable air flow for the car in Item 13 Table 1 would improve fuel consumption significantly, especially at low loads.

The 11th WHEC shows increasing interest in on-board methanol, either as a fuel reformable to hydrogen or for direct use in FCs:

- Cleghorn et al. (1996) show in laboratory tests a significant increase in CO tolerance at anode (to more than 100 ppm in H_2 reformed from methanol); separate tests show a record high performance of direct methanol-fueled PEM FC
- Mantegazza and Maggiore (1996) show successful operation of a small PEM FC on H_2 with 500 ppm CO
- Fischer et al. (1996) maintain that the PEM FC is intolerant to CO concentrations higher than 10 ppm,
- Ekdunge and Råberg (1996) reported favorably on FC, but points out that near-term reformer/FC combinations create considerable global NO_x, HC, and particulate emissions.

The FC, like its related storage battery (the FC is simply a battery with autonomous fuel supply and waste removal), provides the motive power to an electric drive system, whose basic superiority to mechanical drives is beginning to be rediscovered:

- The torque of an electric motor can be roughly constant up to base speed, allowing smooth starts and strong acceleration up to the maximum speed of the motor (but higher-speed motors need to be developed; the availability of on-board cryogenic cooling should help).
- The individual wheel drive becomes feasible without the gearing of mechanical drives, and today's power electronics can provide proper control under a wide range of driving conditions; Wurster et al. (1996) state that wheel-mounted drive motors are now being investigated for the city bus planned in Item 10 Table 2, as this would permit a 100% low-floor solution.
- Noise levels can be much reduced (but air blowers for FCs need improvement in this respect).

- There is higher efficiency at low loads, such as in city traffic.

4.3 Hybrid Power Systems

So far we have assumed that the motive power for transport applications is concentrated in one unit (ICE or FC), covering all ranges of speed, torque, and power required by the vehicle's drive system. Under urban driving conditions, the variation in these parameters can be large indeed, and the inevitable matching between the power unit and the drive wheels is a task assigned to the gear system, both gearbox(es) and differential(s). The versatility of the ICE with conventional fuels has allowed this flexibility, which may be difficult to maintain on hydrogen.

Another approach to this matching question can be provided by hybrid systems, which assign to the prime mover a steady-state, constant speed and power regime approximating the average power required by the vehicle under average load. Thereby the ICE or FC can be considerably reduced in size; a typical passenger bus in a hilly city, for example, can have a peak power about four times that of the average. The intermittent need to provide greater than average power is a task assigned to an energy storage system that would today be electric storage batteries feeding the same main drive motor as would the generator attached to the ICE, or as would the FC. The storage batteries are recharged semicontinuously by the ICE generator or FC when it operates below its rated load, and under braking conditions when the drive motor becomes a generator.

Hybrid systems have recently been introduced into urban buses for emission control on conventional diesel fuel: not only is the engine size reduced but its combustion and emissions are optimized for constant speed and power. Berta et al. (1991) give the results of one such system, now being marketed to industry. This particular bus can even manage for a limited time on storage batteries only, such as town centers or other areas in need of reduced pollution.

Ekdunge and Råberg (1996) examines a standard five-passenger Volvo car equipped with a 75-kW FC and 41-kW Ni-hydride battery that provide an overall peak power of 93 kW.

Other storage devices, especially flywheels, have been proposed but are not yet at the same level of industrial maturity; a few transport authorities seem interested in the concept because flywheels could offer space advantages over present storage batteries. Specialized firms are marketing these devices (Heidelberg 1989), but the literature does not yet give convincing evidence of reliable operation in public service.

An attempt is underway to apply such an energy storage device on a public bus in Munich, but little experience has been reported. Table 2, item 11, is a planned application on a hydrogen bus. Wurster et al. (1996) now quote this bus as having a 60-90 kW PEM FC and a magneto-dynamic flywheel storing 2 kWh of energy and able to provide 150 kW peak. McKenzie (1994) illustrates the impressive promise and plans of several developers in the United States. Hoolboom (1994) actually proposes a flywheel for full power requirements of a car, but gives few concrete results.

One storage device, which more resembles batteries, is electrical capacitors, which are not yet available with large enough storage capabilities, but which are being intensively investigated by some Japanese car manufacturers. Dowgiallo and Burke (1992) give a technology update.

All this can have a profound effect on the optimum ICE for hydrogen vehicles. Many of the objections and difficulties noted in section 4.1 for ICEs with hydrogen are strongly reduced if the engine operates under constant conditions to meet only the average load. The fact that the way can be paved by traditional ICEs and conventional fuel is a major advantage (Berta et al. 1991).

Such a development also smooths the path for FCs, which are expensive and easier to assemble at present in reduced sizes. So an FC only one-fourth the size of that required in a non-hybrid bus may be attractive, depending on cost trade-offs between the FC and the energy storage device.

Wurster et al. (1996) describe two buses for near-term demonstration, of direct interest to this question: the Neoplan one mentioned above with a flywheel energy storage (Item 10 Table 2) and a similar MAN city bus (Item 11 Table 2) in which a 120-180 kW PEM FC provides all power; they will be demonstrated in parallel in the same city.

Schock et al. (1996) find hybrid vehicles particularly suited to compete with conventional automobiles in California. A small, constant-speed ICE with suitable buffer storage (flywheel, ultracapacitors, and batteries are mentioned) gives similar performance to conventional automobiles, and allows "equivalent" ZEV standard (<10% ULEV), until a suitable FC allows full ZEV standard.

The much-reduced requirements for on-board hydrogen storage are also noteworthy, although the weight and space recovered may not be sufficient to compensate for some storage batteries, especially those of the present generation. More compact storage systems, such as advanced batteries, capacitors, and flywheels, must be brought to the market for the hybrid systems to flourish.

A last word in favor of hybrids: their limp-home capability. This would be of strong advantage during an early phase of hydrogen vehicles, because it can guarantee enough autonomy for the vehicle to reach the nearest service station for refilling or maintenance. As noted at the end of Chapter 3, it overcomes a problem following events that lead to complete loss of H_2.

4.4 Ongoing Projects

This chapter ends with an overview of the ongoing projects that use hydrogen-only fuel, and whose intention is to carry passengers on public roads during the mid- and late 1990s. This is at least a concrete measure of how the combinations of fuel storage, prime movers, and other devices are judged to be the most promising. Table 1 summarizes ongoing (mid-1990s) demonstrations by giving a simple description of full-size hydrogen vehicles in operation at that time, together with the results available. More updated projects being prepared for operation in the later 1990s are indicated in Table 2. These tables are self-explanatory, and the references should help interested parties contact the promoters.

Some overall observations may be appropriate:

- More mid-1990s operating projects are found in Europe than in Canada, the United States, or Japan.
- More late 1990s projects are firmly planned in Canada and the United States than in Europe; Japan is noncommittal. However, "firmly planned" is open to change and doubt.
- More ICE than FC projects are being demonstrated in the mid-1990s in both Europe and Japan; in Canada and the United States the emphasis is on FCs, both operating and planned.
- Only one ICE, but four FC, projects are planned in Europe for the late 1990s.
- LH_2 is the favorite in Europe and Japan, but does not yet appear in any Canadian or U.S. projects.
- City buses are the preferred vehicles for demonstration in Europe and the United States; Japan is limiting attention to cars and light trucks.

TABLE 1

ACTUAL HYDROGEN VEHICLES in DEMONSTRATION (mid-1990's)

The Table illustrates only those H2-only vehicles presently in demonstration, ignoring those already phased out or still in planning (see Table 2 for latter)

	1	2	3	4	5	6	7	8	9
ITEM	**DEVELOPER**	**CO-SPONSORS**	**ON-BOARD HYDROGEN STORAGE**	**POWER UNIT**	**VEHICLE**	**RANGE km**	**FIRST TEST**	**OPERATIONAL RESULTS**	**REFERENCE SOURCE and COMMENTS**
- EUROPE: INTERNAL COMBUSTION ENGINES -									
1	BMW Munich Germany	-	8.5 kg LH_2 in 1 cryo tank in trunk; Total W 60 kg, V l; buildup to <2% boiloff/d	Modified standard 6-cyl. gasoline engine, 2.5 to 5 l, 80-150 kW on H_2 at :1 compr. ratio; ext. mix form. (inlet pipe inj. of cryo GH_2) with mechanical supercharger	5-passenger car	400 (highway)	1990	~30% power loss compared to gasoline engine. Emissions: No_x; traces of CO and HC. Refuelling time down to 10 from 60 minutes.	Regar '89, Reister '92, BMW Press Releases
2	Daimler-Benz Stuttgart Germany	BMFT (Hypasse)	40 kg GH_2 at 300 bar in 13 roof cylinders; Total W 2.5 T (incl. extras), V ~2000 l	Modified standard 6-cyl. Diesel engine, 12 l, exh. gas turbocharger, 220 kW (as Diesel) on H2 at 10.4:1 compr.ratio; low-pr. (40 bar) int. mix. form.	70-passenger low-floor 12 m citybus	200 (urban)	1995	Compared to Diesel, power curve similar, torque curve lower at lower revs.: Emissions as % of EURO-II Std.: NO_x 10.4; CO and HC <1 without catalyst.	Jorach '95, Zieger '95 Since '73 M-B H2 vehicles with MH , now GH2; >800 000 km; PROJECT CANCELLED 1996 (see Item 9, Table 2)
3	MAN Nuremberg Germany	- Eur. Comm. (EQHHPP) - Govt. Bavaria	40.5 kg LH_2 in 3 cryo tanks under chassis; Total W 365 kg, V 800, 6%/day boiloff	Modified standard 6-cyl. natural gas engine, 12 l, 140 kW max. on H_2 at 8:1 compr. ratio; external mixture formation (inlet pipe injection of cryo GH_2), no supercharging	92-passenge high-floor 12 m citybus	250 (urban)	1996	?	MAN Brochure Hannover Fair '95 A 2-year demonstration is planned in Erlangen and Munich
4	1.VCST-Hydrogen Systems Belgium 2. Messer Griesheim Germany	- Eur. Comm. (EQHHPP) - Flemish Govt.	18.8 kg LH_2 in 1 cryo tank; Total W 80 kg, V 125 l; 2%/d boiloff	Modified standard 6-cyl. Diesel engine, 11.4 l, 86 kW max. on H_2 at 9:1 compr. ratio, external mixture formation, no supercharging.	88-passenger high-floor 12 m citybus	150 (urban)	1993 (1994 on LH_2)	The 1993 test used MH not LH_2 storage. Results with LH_2 show for European 13-mode test: 0.25 g NO_x/kWh; CO, CO_2, HC, H_2 undetected	Vandenborre '95 See also Item 13, Table 2
5	ENEA Casaccia Italy	-	6.7 kg GH_2 at 200 bar in 8 Al cyls. under chassis; Total W 463 kg, V >400 l.	Modified standard 4-cyl.gasoline engine, 2 l, 45 kW on H_2 at 8.5:1 compr. ratio; ext. mix. form. (inlet port inj. of 7 bar H_2) with water injection.	8-passenger Van/Minibus	150 (urban)	1994	?	Ciancia '94 Future uncertain
- EUROPE: FUEL CELLS -									
6	1. Ansaldo Ricerche Italy 2. Messer Griesheim Germany	- Eur. Comm. (EQHHPP) - City of Brescia	45 kg. LH_2 in 3 cryo tanks on roof; Total W 1100 kg, V 2000 l, 1 - 2%/d boiloff	40 kW DeNora PEM FC with 100 Ah Pb-acid batteries in hybrid layout; 120 kW (nom.) 150 kW (max) AC drive motor	100-passenger high-floor 12 m citybus	300 (urban)	1996 (?)	Only 9 passengers for initial licence	Dufour '93, Marcenaro '94 A lake boat version is also being demonstrated
7	1. Elenco Belgium 2. Air Prods. Holland 3. SAFT France 4. Ansaldo Ric. Italy	Cities of - Amsterdam - Brussels.	50 kg. LH_2 ?	78 kW A FC with 80Ah Ni-Cd batteries in hybrid layout; 180 kW(nom.) 206 kW (max.) AC drive motor	80-passenger low -floor 18 m citybus	300 (urban)	?		De Geeter '94 PROJECT CANCELLED after 200 h. of operation
8	KfK Karlsruhe Germany	-	8.4 kg LH_2 in 1 cryo tank at rear; Total W 219 kg, V l; 2%/d boiloff; + 79 kg LO_2	17.5 kW Siemens A FC with 75 Ah Pb-acid batteries in hybrid layout; 17kW (nom.) 23 kW (max.) DC drive motor	0-passenger Van	> 500 (urban)	1988 1994 on LH_2	The 1988 tests ran on GH_2 (and GO_2). By 1995 a total of 418 h FC operation with 3345 km diff. road tests of diff. length. Avg. FC eff. 50-55%.	Staschewski '95. PROJECT TERMINATED

TABLE 1 (continued)

ACTUAL HYDROGEN VEHICLES in DEMONSTRATION (mid-1990's)

This Table illustrates only those H2-only vehicles presently in demonstration, ignoring those already phased out or still in planning (see Table 2 for latter)

	1	2	3	4	5	6	7	8	9
ITEM	DEVELOPERS	CO-SPONSORS	ON-BOARD HYDROGEN STORAGE	POWER UNIT	VEHICLE	RANGE km	FIRST TEST	OPERATIONAL RESULTS	REFERENCE SOURCE and COMMENTS
				- USA: INTERNAL COMBUSTION ENGINES -					
9	Hydrogen Consultants Inc. (Co, USA)	-SC-AQMD -Univ. Calif. -Electrolyzer	kg GH_2 at 248 bar in 1 composite tank in ; Total W kg, V l	Modified standard 4-cyl. gasoline engine, 2.3 l, kW on H_2 at :1 compr. ratio; ext. mix form. (constant vol. inj. to inlet port); turbocharger	3-passenger Pickup Truck	?	1995 ?	~ % power loss compared to gasoline engine. Emissions (g/mile FTP Test):0.37 NO_x, 0.0 CO, 0.01 HC	Fulton '95 Planned also for Item 7 Table 2.
				- CANADA/USA: FUEL CELLS -					
10 a	Ballard Power Systems (B.C., Canada)	-CANMET -Govt. B.C.	22 kg GH_2 at 207 bar in Al/fibreglass cyls. under chassis; Total W kg V l	120 kW Ballard PEM FC without energy storage/hybrid layout; 80 kW (nom.) DC drive motor, 2.1 bar air compressor.	20-passenger high-floor 10 m citybus	160 (urban)	1993	Cold startup in <4 secs, traction power min. to max. in 0.1 secs.,gradients >15%, top speed 70 km/h, noise level 70 dB at 50 ft	Howard '93, Beck '94, Howard '95
b		-CANMET -Govt. B.C. -BCTransit -SC-AQMD	66 kg GH_2 at 248 bar in composite graphite/polymer cyls. on roof	260 kW Ballard PEM FC without energy storage/hybrid layout; 160 kW (nom.) DC drive motor; 2.1 bar air compressor	60-passenger low floor 13 m citybus	over 400	1995	0 - 50 km/h in 19 secs., starts on 20% grade, top speed 95 km/h	Ballard Brochures Seven further buses will be operated as given under Item 1 Table 2
11	H Power Corp. (Wash. DC, USA)	-US DOE -Georgetown Un. -SC-AQMD -others	On-board reforming of methanol	50 kW PA FC with 170 Ah Ni-Fe batteries in hybrid layout; 2x30 kW (nom.) DC drive motors with total peak power of 108 kW.	20-passenger high-floor 8m citybus	(N.B. methanol)	?	?	Kevala '89, Rossmeissl '95 Last reference mentions 3 such buses in service: 1 at Georgetown Univ., 1 in Los Angeles, 1 at H Power Corp.
12	Energy Partners (FL, USA)	-SC-AQMD	9.8 kg GH_2 at 207 bar in 1 Al/composite cyl.	21 kW Energy P. PEM FC with 83 Ah Pb-acid batteries in hybrid layout; 26 kW DC drive motor; 1:4 bar air compressor (3.5 kW)	1-passenger car	100 (urban)	1994	15 secs startup; 100 miles parking-lot only driving; 0-30 mph in 10 secs, top speed 60 mph, noise level 85 dB at 1 m.	Nadal '94 Updated FC (1996) gives 150% increased output in a project with Ford and US-DOE.
				- JAPAN: INTERNAL COMBUSTION ENGINES -					
13	Musashi Inst. of Technology Tokyo	Nissan	7.1 kg LH_2 in 1 cryo tank in trunk; Total W 60 kg, V l, %/d boiloff	Modified standard 4-cyl.Nissan Diesel engine, 3 l, kW on H_2 at 13.5 compr. ratio; high-pr (10 MPa) int. mix. form.; no supercharging	1-passenger sports car (Musashi-8)	300	1990	The only performance data refer to a top speed of 130 km/h. Operated until late 1995	Furuhama '91
14	Musashi Inst. of Technology Tokyo	Hino Motors Iwatani Int.	25.6 kg LH_2 in 1 vert. cryo cyl. behind cabin; Total W 400 kg, V 1700 l, %/d b-o	Modified standard 6-cyl. Hino Diesel engine, 6 l, 118 kW on H_2 at 13:1 compr. ratio; high-pr (10Mpa) int. mix. form. with 10% EGR	1-passenger 4T Refr. Van (Musashi-9)	500 (less if park and refrigerated)	1994	Refrigerator performance met. In 13-mode driving pattern, NOx only 53% of target and CO, HC almost zero.	Hiruma '93, Yamane '94, Hiruma '95
15	Mazda Motor Corp. Hiroshima	-	3.4 kg H_2 in 20-cell MH tank in trunk; Total W kg, V l.	Modified 2-rotor Mazda 13-B rotary engine, 2 x 654 cc, 96 kW on H_2 at :1 compr. ratio; ext. mix. form (delayed GH_2 inj. to inlet ports)	4-passenger car	230 (highway)	1995	?	Mazda Brochures A Mazda press release in May 1995 states that road test now licensed at steel works supplying the H2; 20 000 km in 2 years in each of 2 Capella Cargo wagon with same engine

Table 2. Hydrogen Vehicles for Demonstration (late 1990s)

This table illustrates only those H_2-only vehicles firmly planned, i.e., with an operating date announced by the developer or operator.

United States/Canada--Fuel Cells

1. Six 40-foot city buses, GH_2, Ballard 205 kW PEM FC, 60-passenger, 400-km range as given in Item 11b in Table 1. BC Transit will operate three of these buses in Vancouver; The City of Chicago, Chicago Transit Authority, and Ballard will operate another three in Chicago.[1]

2. Eight municipal vehicles, 139-bar GH_2, three with 8-kW and five with 4-kW PEM FC, 32-km range for 4 kW vehicles. The City of Palm Desert, California, will test these vehicles in an integrated system of wind power, electrolysis, and H_2 pipeline to refueling station, in the next couple of years.

3. Two airport cargo vehicles, GH_2, Energy Partners 7.5-kW PEM FC, 1-passenger, 3 h continuous travel and 15-min refill time. Los Angeles International Airport, SCAQMD, Schafer Associates, Energy Partners, Air Products, and Ogden Aviation will operate these vehicles in 1997.[2]

4. One transport vehicle, methanol/GH_2, Ballard 45-60-kW in three phases; phase 1 tested a 10-kW FC on methanol/GH_2; phase 2 tested a 30-kW FC. General Motors is expected to operate the full-size vehicle in the near future.

5. Three different light-duty vehicles, H2-fueled, 50-kW PEM FC, in evaluation. Ford Motor Detroit and others (including International Fuel Cell, MTI, Energy Partners, H-Power Corp. for the FC) are currently evaluating the power plant. Once evaluation is completed, a decision will be made about placement of the FC in a vehicle.

United States--Internal Combustion Engines

6. Three pickup trucks, 248 bar GH_2, H_2 Consultants CVInjection, three passengers. Xerox and others will test these vehicles at the El Segundo, California, facilities in an integrated system of photovoltaic hydrogen production, storage, and distribution.[3]

7. One 33-foot city bus, 3-ton La-Ni MH, Ford V-8 engine, 32-passenger, 240-km range.[4]

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[1] Since the preparation of this table, the buses have gone into operation in both Vancouver and Chicago.

[2] These vehicles were successfully operated in 1997.

[3] This demonstration was successfully completed in 1997.

[4] The bus was demonstrated in 1997.

Table 2. Hydrogen Vehicles for Demonstration (late 1990s) (continued)

Europe--Fuel Cells

8. Unspecified Mercedes Benz buses with FC, adopted following cancellation of item 2 in Table 1.

9. One Renault Laguna passenger car, 8 kg LH_2, 30-kW PEM FC, 500-km range.

10. Air Liquide, Ansaldo, DeNora, Renault will test this vehicle in 1997[5]. Wurster et al. (1996) give further data on the bus: 100 passengers, low floor, 150-300 km/d, 2.2 m^3 GH_2 at 25 MPa in 12 composite rooftop vessels, 60-90 PEM FC in hybrid combination with magneto-dynamic flywheel, two wheel-mounted drive motors. Demonstration in Erlangen (see also Item 3 Table 1) from early 1999 with 50% co-financing requested from federal and state governments. (See Appendix 4 for more details.)

11. One MAN city bus, 12 m, 100 passengers, low floor, 150-300 km/d, 2.2 m^3 GH_2 at 25 MPa in 12 composite rooftop vessels, 120-180 kW PEM FC, single central drive motor. Demonstration as for Item 10 above. (See Wurster et al. [1996] and Appendix 4 for more details.)

12. One Peugeot minivan, 30-kW PEM FC, 500-km range. Ansaldo, CEA, DeNora, Peugeot will test this vehicle by 1998.

Europe--Internal Combustion Engines

13. One low-floor Van Hool midibus, original gasoline engine modified by VCST-Hydrogen Systems to 108 kW with supercharger, 350 liter LH_2 tank on roof, 70-passenger, 200 km range. De Lijn will operate this bus in Ghent, Belgium in 1996; refueling from a 6000 liter LH_2 tank in bus depot.[6]

Japan--Fuel Cells/Internal Combustion Engines

None announced.

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[5] Testing was completed as scheduled.

[6] Testing was completed as scheduled.

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Appendix 1. Safety Questions of Hydrogen Storage and Use in Vehicles

This Appendix shows the available findings on the safety concerns and solutions when hydrogen is stored on-board and used in road vehicles. Other situations with different safety implications, such as large-scale stationary hydrogen storage, will not be explicitly handled.

Until operating data are accumulated with hydrogen vehicles, the best approach is to examine the following:

- The fundamental properties of hydrogen with safety relevance
- The experience to date from comparable industries (including space)
- Recent simulations of specific accidents with H_2 vehicles.

Undoubtedly laymen, and even many technically informed people, react to hydrogen as a particularly dangerous substance. Yet insiders are becoming ever more convinced that hydrogen has a safety behavior different, but no worse than, conventional transportation fuels. It is probably safer overall, provided some basic rules are followed. The public reacts with some skepticism to such affirmations, and great care will be needed in presenting the situation in a balanced and convincing way. This means paying considerable attention, when the time comes, to societal concerns as well as to technical aspects.

Much technical work remains to be done to assure even the specialist that hydrogen vehicles can be safely used by the public. This report concentrates on the technical aspects; however, societal concerns should be factored rather soon into remaining developments. The reaction provoked by others such as the nuclear industry, which underrated the need to address legitimate public concerns, should be avoided at all costs.

Hydrogen has routinely been used in large quantities for decades in the petroleum refining, chemical, and petrochemical industries with no serious problems. Moore 1996, summarized in Appendix 4, gives relevant experience in the USA. The space industry has a similar record, marred only by the Challenger accident (discussed in section A1.4).

The manner in which safety objectives have been met by these industries is outlined below. This experience is largely applicable to hydrogen vehicles, but has in this context one important weakness: the public was not involved, and all procedures were safely in the hands of qualified personnel. The safety consciousness typical of such industries can be brought to high levels by training and automatic control, but is difficult to transfer to the public.

For the foreseeable future, highway driving will be subject to unpredictability, and accidents to confusion and panic. A new fuel should possess better inherent safety than gasoline or diesel oil. Somewhat paradoxically, hydrogen has such characteristics, at least to the specialist. A large part of the following discussion will therefore involve comparisons with traditional fuels.

This appendix was written before an important, but unpublished, report (EQHHPP 1993) was made available after the update was due to the 11th WHEC. Although we could not examine the implications of this report throughout this document, we have been given permission to quote its summary here:
In brief, the study comprises:

- a compilation of physical and chemical properties of hydrogen
- a description of hazards
- a collection of international and national rules, discussed in varying depth
- a number of recommendations for further development of rules and their international harmonization
- proposals for the promotion of hydrogen, and the proper approach of the public in the early phase of industrial projects
- standards and their relevance for selected items of the EQHHPP (in the appendixes)

A1.1 Fundamental Hydrogen Properties with Safety Relevance

Fischer and Eichert (1995) provide an updated critical review of the data (mostly experimental) that affect the behavior of hydrogen in situations relevant to safety. Though general, this review repeatedly illustrates how the behavior can be greatly affected by the initial and boundary conditions, i.e., the specifics of each accident. Fischer et al. (1996) state that today modeling and simulation show good agreement with a variety of fast combustion phenomena observed in experiments. One useful result would be the design of improved detonation arrester geometries. Sanai (1996) proposes an accident analysis algorithm, based on available experimental data and computer simulation of explosion accidents, to quickly calculate the response of humans and structures to such accidents. Maas (1996) handles phenomena such as auto ignition, induced ignition, minimum ignition energy, the transition from deflagration to detonation, and catalytic combustion, and concludes that the rapid improvements in numerical simulation and computing power will soon allow good simulation of practical combustion systems with complex geometry. Kratzel (1996) also models the processes leading to detonation, especially in complex geometries, among the most challenging to hydrogen safety. Table 3 is a selection of parameters from Fischer and Eichert (1995) and Kalyanam and Moore (1987).

Table 3. Safety-Related Properties of Hydrogen and Conventional Fuels

Property	Unit	H_2	CH_4	Gasoline	Diesel
Gas density	g/l NTP	0.08	0.65	4.4	-
Lower heating value	kWs/g	120	50	44	43
Stoichiometric composition in air	vol. %	29.5	9.48	1.75	-
Buoyant velocity in air	m/s	>1-0	>1-6	nonbuoyant	nonbuoyant
Self-ignition temperature	°C	585	540	230-470	251
Flame temperature in air	°C	2045	1875	2200	
Ignition limits in air	vol. %	4-75	5-15	1->7	<1->7
Minimum ignition energy	mWs	0.02	0.29	0.24	-
Flame speed in air	cm/s	-295	-41	-40	-
Flame thermal radiation	%	17-25	23-33	30-42	-
Maximum safe gap in air	mm	0.08	1.2	0.7	-
Detonation limits in air	vol. %	18-59	>6->13	>1->3	
Detonation velocity in air	km/s	-1.8	-1.5	-1.6	-
Theoretical explosive yield per m^3	kg TNT	2.02	7.03	44.22	-

It is not advisable to rate the above properties according to their importance to safety. Many authors focus on the ease of ignition (limits and minimum energy for ignition), the speed of combustion, the potential for detonation, and so on, as of particular concern. But closer examination can easily re-dimension the apparent gravity of these factors:

- The lower ignition limit guides the evolution of most fires, and there is little difference between the various fuels; in fact, propane has the lowest limit.

- The minimum ignition energy is indeed lower for hydrogen by an order of magnitude, but any real-life ignition source (electrostatic discharge, etc.) has an energy content higher than the minimum for the other fuels, so again fires can start just as easily with the other fuels.
- Although the detonation limits and velocity are in general higher for hydrogen, the explosive energy of the much less dense hydrogen in air is considerably less.

Rather than continue this comparison of basic properties, it is much more instructive to proceed by illustrating hydrogen experience from more traditional industries, analyzing recent integral safety testing for hydrogen vehicles, and reviewing the findings from the investigation of the Challenger accident.

A1.2 Hydrogen Safety Experience from Traditional Industries

The most comprehensive treatment available to us[7] on this subject is the *Safety Guide for Hydrogen* published by the National Research Council Canada (Kalyanam and Moore 1987). It is required reading and reference for anyone in the field. The main chapters are highlighted here.

A1.2.1 Classifying Hydrogen Hazards

The known hazards associated with hydrogen can be classified under the following headings:

- Leakage and spillage
- Combustion
- Detonation
- Reactions with oxidants, halogens, and metals
- Metal embrittlement
- Asphyxiation
- Cryogenic hazards

A1.2.2 Methods for Reducing Risks

The general industrial practices and guidelines for reducing risks in hydrogen systems are:

- Comply with codes, standards, and guidelines.
- Limit quantities for indoor storage.
- Locate and separate process and storage equipment.
- Control hydrogen accumulation within enclosures.
- Exclude air.
- Eliminate ignition sources.
- Detect and control leakage.
- Contain LH_2 spills.
- Verify instrumentation.
- Verify safety reliefs.
- Vent and dispose safely.
- Select proper construction materials.

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[7] As already mentioned, the unpublished report EQHHPP Nov. 1993 would supersede this since it is in effect an updating of the available safety information and methodology, and includes a valuable survey of the international regulations, as well as the national ones of 6 countries of Europe and North America; it also addresses the societal concerns regarding hydrogen safety.

- Take cryogenic precautions.
- Detect, control, and extinguish fires.
- Identify and assess hazards.

Linney (1996) is a study of quantified risk assessment techniques in optimizing the safety features of on-board hydrogen systems. One important conclusion is that, in many real hydrogen leak scenarios, high release velocities and normal ambient winds overshadow the buoyancy/diffusivity advantages.

A1.3 Recent Safety Analysis and Integral Safety Testing for H_2 Vehicles

For illustration, three projects will be reviewed from which we can extract relevant safety information:

- MAN full-size city bus fueled with LH_2, and now ready for public demonstration
- BMW integral testing in severe accidents with LH_2 tanks
- Urban LH_2 refueling station.

(On-board GH_2 and metal hydride storage is discussed in section A1.3.4.)

A1.3.1 Safety Analysis for MAN LH_2 City Bus

This bus is identified as item 3 in Table 1, which compares the characteristics and performance, if available, of ongoing demonstrations of H_2 vehicles.

The LH_2 bus is a modified MAN 6-cylinder, 12-liter, natural gas engine, able to develop 140 kW maximum on H_2 with 8:1 compression ratio; external mixture formation with sequential multi-port injection. When full the three LH_2 cylinders, accommodated under the bus, contain about 40 kg of fuel, have a total weight of about 300 kg and a volume of 630 liters; they suffer 6% boil-off per day. Ninety-two passengers can be carried in urban service with a range of 250 km.

MAN engineers have carried out a fairly detailed risk assessment for this bus, in the form of a Hazops study (a hazards and operation analysis), in which engineering judgment substitutes, to some extent, the detailed statistics needed for a full-blown probabilistic risk assessment. The Hazops study was carried out in collaboration with the regulatory authority of Bavaria on the accident scenarios and the countermeasures needed to guarantee safety.

This approach, based on engineering judgment of possible accident initiators and their development in the system, was then extended to a worst-case scenario in which logic and engineering judgment are put aside, and an accident scenario is maximized to identify extreme countermeasures. This scenario is intended to answer the severest critics of the system's safety.

The worst case imagined was the rupture of a single tank filled with LH_2.

A1.3.2 BMW Simulations of Severe Accidents with LH_2 Tanks

In the absence of probabilistic risk assessments, or of the more simplified Hazops studies, an approach often taken to accident analysis is to identify a series of worst-case scenarios, in which the originating cause of an accident and its logical progression are ignored, and attention is focused on its ultimate consequences.

The tools used can be analytical, if enough differential data are available; more often with a new technology, an experimental approach is adopted whereby the ultimate event is simulated and the consequences observed on the component or system. Thus BMW has taken LH_2 tanks of the suppliers Linde and Messer Griesheim, and subjected them to such worst-case testing. Typical LH_2 tanks, such as those foreseen for BMW cars under Item 1 of Table 1 were subject to extreme bursting loads (Pehr 1995).

In Pehr (1996) we find essentially the same presentation on a range of tests in two separate parts:

- Abrupt release of LH_2 at 2.5 times operating pressure at a deliberately weakened location
- Potential releases by pressure buildup, fire, or mechanical damage.

A1.3.3 Urban LH_2 Refueling Station for 120 City Buses

Würsig (1996) overviews safety analyses of a Hazops-type, carried out for various facilities for LH_2 transport, storage, and use in Hamburg. The refueling station of interest here is not reported in detail, but Würsig concluded that it, and the other facilities, could be completed from a safety perspective, and that operational benefits resulted from the safety analysis.

A1.3.4 Safety of Hydrogen Vehicles with GH_2 or Metal Hydride Storage

We have not found detailed safety analysis or testing for H_2 vehicles with compressed gas or MH storage. This does not mean that such analysis has not been done, and there is every reason to believe that responsible transport authorities (H_2 buses are the main object of near-term demonstrations), as well as the regulatory authorities have done their jobs in this respect.

Until we see convincing analytical and test results, similar to the above ones for LH_2, it would be premature to offer any comparison. Even apparently reasonable statements such as that the hydride form, having little free hydrogen and then only by deliberate application of heat, is obviously the safest, must be treated with care until backed by rigorous analysis and testing. For example, what happens during a large-scale fire? Perhaps only a slow release and combustion of hydrogen, together with the metals involved. But proof is needed, and if available it should be published.

Zieger and Krämer (1995) do, however, give some overall results of safety tests, carried out by Daimler-Benz in collaboration with TüV Bayern Sachsen on the 300 bar GH_2 cylinders of item 2 in Table 1. A series of burst tests, fire tests, 1.2 m drops, missile and alternating loads gave satisfactory results.

Finally, a word is needed on so-called environmental impact statements, which are often required when large-scale application of a new technology or process is proposed. Besides safety analysis and test results, the hydrogen statement must be completed with other information such as toxicity, sabotage, and so on when more than single vehicles are proposed, say when small fleets are in discussion for the first time.

We have every reason to believe that no unforeseen problems will arise with hydrogen, and we know that some aspects such as toxicity and carcinogens are indeed superior. But accurate data must be gathered and rigorous tests conducted before the final impacts can be assessed. This is particularly true if the full cycle of hydrogen production and use is considered, although this would normally go beyond the means and motivations of the average transport authority.

A1.4 The Challenger Accident

Certainly the space industry, and the Shuttle program in particular, cannot be compared with the more mundane activities of traditional industries, including a future hydrogen vehicle industry. Yet when such a common factor as safety of human life is involved, we must ask ourselves whether the chances of failure cannot be similarly high.

Feynman (1986), an eminent scientist who formed part of the Presidential Commission that investigated the accident, stated:

> *If a reasonable launch schedule is to be maintained, engineering often cannot be done fast enough to keep up with the expectations of originally conservative certification criteria designed to guarantee a very safe vehicle. In these situations, subtly, and often with apparently logical arguments, the criteria are altered so that flights may still be certified in time. They therefore fly in a relatively unsafe condition, with a chance of failure of the order of a percent (it is difficult to be more accurate).*
>
> *Official management, on the other hand, claims to believe the probability of failure is a thousand times less. One reason for this may be an attempt to assure the government of NASA perfection and success in order to ensure the supply of funds. The other may be that they sincerely believed it to be true, demonstrating an almost incredible lack of communication between themselves and their working engineers.*

This indictment may be peculiar to the space industry, but a skeptical public may not be so persuaded.

The cause of the accident was simple enough. A rubber O-ring, intended to prevent hot gases from escaping through a joint between two lower segments of the solid rocket booster, could not expand properly at the cold ambient temperature of this launch. The escaping gases from the aluminum-based fuel booster acted as a torch, breached the LH_2 tank and ignited the hydrogen, resulting in the destruction of the vehicle.

The psychological and other pressures on NASA differ from those on the automotive industry. But public relations, the strife of competition, and so on, can stifle the automotive engineer's voice. If hydrogen with its new--not necessarily increased--risks is to become the fuel of the future, the safety culture in the organizations involved may need to be updated.

Appendix 2. Performance of Hydrogen-Fueled Internal Combustion Engines for Road Vehicles

During the century or so that the ICE and automotive transport have been such dominant features of life, there has been little difficulty in suitably matching fuels (usually gasoline or diesel oil, but also other hydrocarbons) and the engine design as it evolved over the decades to meet higher performance and environmental objectives.

The end of this process is in sight, partly because the overall smog levels in many modern cities are becoming intolerable–the increase in vehicle population far outstrips the diminishing improvements per vehicle--and partly because the CO_2 and other molecules cannot be removed and are held responsible for much-discussed climate change.

It is worthwhile, however, to review briefly the manner of combustion in four-stroke Otto (gasoline) and diesel engines, which represent the bulk of ICEs in use, because the performance of hydrogen fuel in these engines will frequently be compared to gasoline and diesel.

A2.1 Combustion Processes in a Traditional ICE

A2.1.1 Four-Stroke Gasoline ICE

On the *inlet stroke*, the air-fuel mixture is drawn into the cylinder from the inlet manifold/inlet ports, originally from a carburetor but increasingly now from gasoline injection into the air at each inlet port; the inlet valves, originally one, now increasingly two or even three, remain open at least throughout the stroke. In turbocharged engines, the air is compressed for better power output and the gasoline pressure suitably adapted.

As the piston rises on the *compression stroke* it swirls the mixture and evaporates the gasoline; the inlet valve is often still open up to 301 after bottom dead center (BDC) for increased charging; compression ratios reach 10:1 or higher requiring additives (lead now being phased out in favor of benzene) to prevent pre-ignition and power loss.

The *expansion stroke* involves combustion and expansion of the gases, whose temperature can reach higher than 1200ºC, but ignition from a spark plug occurs before top dead center (from about 51 to 501 BTDC) as the engine speed increases to give enough time for proper combustion. The spark is automatically advanced by electronics compared to earlier mechanical devices; only 1001 crank angle (or a few milliseconds at high revs) are then available in the compression stroke (between 301 ABDC inlet valve closure to 501 BTDC spark) for full vaporization of the gasoline (which burns satisfactorily only as a gas); hence the importance of swirl and squish and the automatic spark advance for good burn.

On the *exhaust stroke,* the exhaust valves (originally one, now often two) are open and the cylinder contents are sent to the tailpipe with prior pollution control (originally only acoustic, now with catalytic converters for unleaded gasoline controlling CO, SO_2, and NO_x down to low levels); the inlet valve usually opens just before TDC to purge the cylinder as much as possible before the exhaust valve closes just thereafter.

A2.1.2 Four-Stroke Diesel ICE

The main difference is that the mixture of air and diesel fuel, which has a low self-ignition temperature (about 250ºC compared to as high as 470ºC for gasoline), is compressed to much higher levels (the compression ratio can reach 18:1 or more) and the spark plug can be dispensed with. Furthermore, diesel oil burns well as a liquid, obviously subdivided into very fine droplets to create a homogeneous mixture.

The air on the inlet stroke is often turbocharged, and brought to 40-50 bar on the compression stroke, raising its temperature to 600-700º C. High-pressure diesel oil is injected BTDC to allow vaporization from the fine liquid drops to start combustion at TDC, and continue at a constant pressure for part of the expansion stroke. Diesel engines generally run at lower speeds than the gasoline versions.

Compared to hydrogen, these fuels--or indeed any other hydrocarbons--displace very little air because the densities of gasoline or diesel oil, even as gases, are quite high. Filling the cylinder with air, and then adding the required amount of hydrocarbon fuel to reach stoichiometry or higher, is no problem; turbocharging adds yet more power to each charge.

A2.1.3 Combustion Processes in a Hydrogen ICE

Hydrogen for ICEs is a much more difficult fuel, first because its very low density means that air is displaced and a given cylinder volume could produce much less power, perhaps only 60% of traditional fuel power. Accepting this disadvantage, the pioneers quickly realized that hydrogen combustion was also much less controllable, reducing the power even more and (perhaps worst of all) producing very audible backfiring and rough running.

This Appendix focuses on the fundamental properties of hydrogen compared to the usual hydrocarbons, which are often the same as those of interest to safety. Table 3 shows the properties.

Some may be surprised at first glance why hydrogen, the first choice for rocket liftoff and flight into space, should perform so poorly in the reciprocating ICE. This is easily explained, however, and is simply the difference between hydrogen's energy content on a weight basis (of overriding concern for liftoff) and on a volume basis (making gasoline more attractive in a given cylinder volume). Rockets usually use oxygen rather than air, further increasing the power.

Table 3 shows three fundamental properties which determine hydrogen's behavior in any ICE:

- The wide flammability limits ensure that almost any air/fuel ratio can be used and still get good combustion; in other words, the air flow into the engine need not be throttled - an advantage, bearing in mind the difficulty of charging air in the first place.
- The high self-ignition temperature of hydrogen rules out the diesel cycle with its higher pressures and efficiency; spark assistance is needed and corresponding space is occupied in the cylinder head.
- The high flame speed of hydrogen, and its readiness to detonate, are the main problems when pre-ignition can occur which, as we will see, are difficult to avoid with low-pressure injection; however, high flame speed is vital when high-pressure injection is preferred.

But these properties and remarks are just the beginning. Much work has been done, and considerable progress made, in testing and demonstrating the various regimes for successfully operating hydrogen/air mixtures in ICEs. The most complete reporting, and therefore perhaps the most wide-ranging approach, have been made by the Musashi Institute of Technology in Japan, which has worked on H_2 combustion since 1970.

Two basic approaches have been taken to obtain a combustible hydrogen/air mixture in the cylinder of an ICE: external and internal mixture formation, each of which in turn is further subdivided into separate lines. In the following sections, the evolution and characteristics of each line are explained, proceeding generally from the simplest to the most complicated, but these designations can change with time and experience.

A2.2 External Mixture Formation

In this approach the mixture of hydrogen and air is formed outside the cylinder, including usually the early part of the inlet stroke. It is thus characterized as being at essentially ambient pressure, and at a temperature from near-ambient down depending on hydrogen storage temperature.

At its simplest, the hydrogen can come from a single device that meters the quantity for each cylinder in turn. This would be analogous to the single carburetor of simple gasoline engines, but has the great disadvantage for hydrogen of making the whole inlet manifold subject to backfire. Somewhat more complicated is the timed injection where each inlet port is supplied with low-pressure hydrogen, limiting the backfire-prone mixture to that in the immediate vicinity of each cylinder. This line also preserves the advantages of multi-port sequential fuel injection as in modern gasoline ICEs: less mixture variation, improved acceleration, better volumetric efficiency, and elimination of the carburetor or similar device, which insert pressure barriers to the mixture.

With low-pressure hydrogen injection typical of external mixture formation, the injectors are relatively simple, and can have a metering function only if the hydrogen storage pressure is high enough (which is usually the case). The air flow is unthrottled, but the incoming hydrogen occupies considerable space because of its low density. Turbocharging the air can help, but the relative power loss of hydrogen compared to gasoline remains as high as 40%. Simple mass considerations show this loss to be at least 15%.

As with gasoline the inlet valve can be closed about halfway through the compression stroke, compression can proceed to about 10:1 ratio, and spark ignition can occur in the final part of the stroke depending on engine speed. The expansion and exhaust strokes proceed generally as in a gasoline engine, but hydrogen and its combustion products with air (essentially only H_2O and small amounts of NO_x) can also lodge in cylinder recesses and be present during the inlet stroke.

At low engine speed and load, hydrogen combustion with external mixture formation proceeds smoothly over a wide range of lean mixtures. Thermal efficiencies are high, and the exhaust contains only trace quantities of NO_x (the low temperatures of lean mixtures block NO_x formation), as well as inevitable traces of CO and CO_2 typical of lubricating oil combustion. Unfortunately, this excellent result starts deteriorating toward mid-powers and speeds with the advent of rough combustion caused by pre-ignition and backfire. The NO_x levels can increase rapidly and power levels typical of gasoline engines cannot be achieved, not only because of hydrogen's low density, but also because of deteriorating combustion.

The phenomena at work in irregular combustion during the inlet stroke have no doubt been investigated by most researchers, but the most complete reporting has been made by Musashi Institute of Technology. Koyanagi et al. (1994) describe the definitive experiments on a single-cylinder engine supplied with hydrogen from a relatively large reservoir with spark plug ignition at 231 BTDC and 10:1 or 12:1 compression ratio. Temperatures were measured by thermocouples near the surface of the spark plug, object lenses followed the luminescence of the flame, recorded either by photomultiplier or by high-speed video camera, and of course crank angle and internal pressures were recorded. They found that:

- Backfiring occurred more easily and frequently with leaner mixtures and at the lower compression ratio, i.e., at lower temperatures.
- The spark plug can be eliminated from consideration as the source of pre-ignition and backfire.
- Special pistons with enlarged radial clearance at top land clearly showed that the exhaust gases trapped in this clearance volume were the source of pre-ignition and backfire.

Because little can be done to eliminate such residual pockets of hot exhaust gas, the Musashi researchers seem to have abandoned external mixture formation, because most of their remaining reports deal only with internal mixture formation. Others prefer to continue with the external mixture formation, and ascribe the backfire to other causes such as spark plugs and hot exhaust valves, but they try to get around the problem by two lines of approach:

- A mechanical/hydraulic one, in which cool air first enters the cylinder, ambient-temperature GH_2 is injected at low pressure, further air flow purges the inlet port of hydrogen, and the inlet valve closes; the low temperatures retard pre-ignition and even if it occurred, the flame does not backfire into the inlet port.
- A cryogenic one, in which low-temperature GH_2 or LH_2 is injected into the inlet port retarding any pre-ignition at least until the inlet valve is closed and backfire becomes impossible.

Proponents of the first system are Hydrogen Consultants of Colorado (USA), which has been converting ICEs (mostly diesels) to hydrogen since 1980, originally for underground mining. Its updated system has recently been presented (Fulton and Lynch 1995), and consists of so-called constant-volume injection (CVI) chambers with slightly-pressurized GH_2 being charged from on-board storage and discharged to each cylinder inlet port in tune with the operating cycle; the absolute pressure ratio between CVI and cylinder is held constant at typically 2.5; the CVI volume is directly related to cylinder volume, and the air/fuel ratio is held constant over a wide range of operating conditions; turbocharging is usually used for heavy-duty engines; second-order effects of ambient temperature, engine volumetric efficiency, etc., are small but are now handled by specialized electronic equipment adjusting the air/fuel ratio, i.e., the GH_2 pressure in the chamber. Item 9 of Table 1 and item 7 of Table 2 are examples of such a system. Backfiring is largely eliminated, and reportedly sounds more like a misfire on the rare occasions when it occurs.

BMW of Munich, Germany, has adopted the second system, with cryogenic GH_2 injection in sequential multi-port operation, and applied it to its larger passenger cars on a trial basis since 1980. This company opened a special test stand dedicated to H_2 vehicles in 1989, with appropriate safety features and equipped with a 3000-liter LH_2 outdoor tank with neighboring filling station. Operating experience with external mixture formation and cryogenic H_2 is being accumulated. Item 1 of Table 1 is the test car that BMW has successfully demonstrated for the past 5 or more years. The LH_2 at about 5 bar is heated in a central exchanger by engine water up to - 1°C, and the resulting cryogenic GH_2 is fed to a central, electrically operated supply valve with electronic control that injects the required fuel to each cylinder inlet port in sequence. The engine runs under lean conditions for all driving conditions, giving high efficiency and very low NO_x emissions. Braess et al. (1990) claim that there is no pre-ignition or backfire, but that a mechanical supercharger had to be fitted to prevent large power loss; even so, there is a 30% power loss compared to the standard engine results.

Similar results are reported by VCST-Hydrogen Systems of Belgium, which has also adopted the cryogenic external mixture formation for its LH_2 Greenbus (item 4, Table 1 and item 13, Table 2).

The final step to high-pressure injection of LH_2 in the second half of the compression stroke is under active investigation, especially in Japan, and in isolated instances in the United States. The challenge must be underlined: LH_2 pumps are notoriously difficult, because of cavitation and lack of H_2 self-lubrication at these temperatures; LH_2 injectors need to seat reliably because any leakage into the cylinder on inlet stroke causes pre-ignition if not backfiring; only a few milliseconds are available for mixing of the cryogenic GH_2 (it becomes immediately a gas in the cylinder or indeed before it reaches the injector) with air; the flame radiates little heat so, in spite of high flame speeds, the single-point spark may not give complete combustion.

A2.3 Internal Mixture Formation

It is clear from the above discussion that external mixture formation has little future if the big step to internal mixture formation can be accomplished.

Internal mixture formation refers to H_2 injection with all valves closed, generally as the piston approaches TDC and before ignition is sparked. It requires pressures as high as 100 bar, especially as the advantage of high compression ratios (higher power and efficiencies) can be exploited. Therein lies the challenge because only LH_2 can be considered (a GH_2 storage system would need to carry a permanent ballast of 100 bar unuseable gas); mixing must be accomplished in very few milliseconds; and cryogenic pumps and injectors when cavitation is always incipient, and the fluid has no lubricating potential, simply do not exist except in experimental versions.

So some projects are starting with low-pressure IMF, where the H_2 is injected after the inlet valve closes but before the pressure rises above 10 bar. The injector technology is not too demanding, mixing has more time to be complete, high compression ratios can be used and, with turbocharging, the power output can be maximized; in fact, power output can approach 120% of the gasoline engine if combustion is smooth. Unfortunately, early (low-pressure) IMF is subject to pre-ignition for reasons mentioned earlier and which Japanese researchers blame on the unavoidable hot combustion products present in the cylinder on the inlet stroke. According to Furahama (1989), this pre-ignition can cancel the 20% theoretical power gain.

Furahama et al. (1991) give details on combustion processes for the Musashi-8 small sports car with a modified four-cylinder Nissan diesel engine illustrated as item 14 in Table 1. This car, the latest in a series of H_2 test vehicles from this leading Japanese institute, was equipped with updated high-pressure LH_2 pump and injector, and relative control: LH_2 pump in the cryogenic tank and powered by a direct current (DC) motor with accurate control of speed and pressure; high compression ratio (13.5), and hence higher LH_2 pressure (10 MPa);separate spark control on each cylinder; injector nozzle with eight holes and actuated by oil pressure; and a combustion cavity in the crown of each piston.

The combustion details were first investigated and adjusted on a single-cylinder optical research engine, similar to a single cylinder of the four-cylinder Nissan engine. Above all, the very crucial values of injection timing and ignition timing--absolute and relative values--were fine-tuned. The combustion processes were visualized through the piston, with mirrors installed on the cylinder head, and on the intake and exhaust valves. High-speed laser-enhanced Schlieren photographs showed density differences in the mixture as it combusted. In addition to the wealth of overall data, it was found that if the eight hydrogen jets are ignited when the nearest tip reaches the spark, combustion spreads smoothly one after the other to the remaining jets, and the cylinder pressure rise is optimized; delaying the spark by only 0.4 ms gave poor combustion. In both cases injection started at 181 BTDC, and spark occurred at 151 (good combustion) or 141 (poor combustion) BTDC.

Applied to the main engine running at higher speed, since the time for the hydrogen jet to travel from injection to spark is constant, a variable but highly precise spark timing allowed good combustion in road tests up to 130 km/h.

These results were then used in a study with two other engines to measure the NO_x emissions, which can in principle be similar in any air-breathing ICE (Ninomiya et al. 1992). The formation of NO_x depends essentially on the flame temperature and duration at high temperature; cooling the mixture and/or retarding the injection timing (for diesels) are well-known methods of lowering flame temperature/duration. Another way, applicable only in H_2 ICEs, is to recycle the cooled exhaust (essentially air and H_2O) so that the heat for water evaporation cools the mixture. The report gives the details of the tests on H_2 ICEs and the results obtained with all three methods, singly and in combination. Ten percent exhaust gas recirculation is sufficient to more than halve the NO_x and to meet the emission standards in force, without any effect on attainable power; a similar result is obtained with cryogenic (-120°C) compared to ambient H_2; a large synergistic effect comes from the combination of exhaust gas recirculation (EGR) and cryogenic H_2; ignition retardation seems overall to have less effect.

These Japanese studies continued with another one by the same team (Koyanagi et al. 1993), taking up surprisingly the external mixture formation in combination with internal direct-injection of LH_2 at higher powers. This is expected to overcome the need for delicate adjustment of injection and ignition timing noted

by Furahama et al. (1991) for high-pressure only injection where, even with eight jets, ignition starts on one jet and proceeds to adjacent ones in turn; it should also avoid the increased NO_x at low speed with internal as compared to external mixture formation. The external mixture formation was expected to speed up the flame diffusion, and in fact, using the optical research engine with Schlieren photography, optimum combustion and minimum NO_x resulted for the entire speed and load range. What is not clear from this dual approach is whether the combined advantages of two injections outweigh the combined disadvantages.
Koyanagi (1993) reported some optimization studies on high-pressure injector variables that affect mixing and combustion: injection pressure, nozzle geometry etc.

Finally, the Japanese team has unveiled Musashi-9, a LH_2 refrigerated and fueled van included in Table 1 as item 15. The original six-cylinder 6-liter engine was modified by replacing the diesel injectors with nine-hole high-pressure LH_2 ones, installing a spark plug, bringing the compression ratio to 13:1 and fitting a piston with cavity of 0.76 squish ratio. The results were good, in particular the NO_x was reduced to very low values (about half the 13-mode target) by slight injection retardation, hot-EGR of 10%-20% with air/fuel ratio of 1.3-1.5 (Yamane et al. 1994; Hiruma et al. 1995).

Other groups are also attempting to adapt the difficult high-pressure LH_2 injection to ICEs. But performance and emissions data are not available on these projects so they cannot be further discussed here.

The 11th WHEC includes several papers of interest to this appendix, and relevant points are included in the main text. In particular, the following papers can be quoted and are summarized in Appendix 4: Fulton (1996), Provenzano (1996), Peschka (1996), Naber (1996), Digeser (1996), Kondo (1996), Valdimarsson (1996), Meier (1996), Brown (1996), Knorr (1996).

Appendix 3. Fuel Cells for Hydrogen Vehicles

The FC is in effect an electrolyzer operating in reverse: instead of an applied DC voltage splitting water into hydrogen at the cathode and oxygen at the anode of the electrolyzer, the FC provides a DC voltage when the electrodes, separated by a suitable electrolyte, are supplied with these gases. Water is produced by electrochemical reaction of the hydrogen and oxygen; no other waste products arise.

Another way to regard the FC is as a storage battery: a DC voltage is supplied by the latter from intermittent charging, while the former does so continuously in the presence of hydrogen and oxygen at the electrodes. The waste products of a battery are, however, often objectionable; an FC emits only water, which can even be used for recycling to the cell.

A3.1 Fundamentals of Fuel Cells

An example of a basic FC consists of two electrodes (hydrogen at the anode and oxygen at the cathode) separated by an electrolyte. The electrolyte blocks the electrons which are released during the oxidation of the hydrogen at the anode. The electrons are forced to travel through the external circuit to the cathode, where the oxygen is reduced. The electrolyte allows easy passage of hydrogen ions (protons), enabling the hydrogen to react with the reduced oxygen at the cathode to form water. As will be seen later, the hydrogen must presently be supplied in a pure form at the anode, but normal air is satisfactory at the cathode.

The open-circuit voltage, i.e., without external load, of an FC is about 1.2 V at ambient conditions. This, however, is an ideal value, and in practice drops to about 1 V at no load, giving a maximum attainable efficiency of practical devices reaching 80%. When the load is increased, the electrochemical reactions proceed rapidly at the anode, but the inherently slower oxygen reactions at the cathode--even when highly catalyzed with precious metals and with increased air flow and pressure--together introduce irreversibility into the electrochemical reactions, and the efficiency drops continuously. Increasing resistive losses in the electrodes and electrolyte cause further losses. The extent of the drop depends on FC type, temperatures, catalysts, current densities, etc., but 50% at full load can be taken as representative of today's technology. Losses in ancillary systems for fuel handling, vehicle services, etc., inevitably cause further drops in overall efficiency.

This deterioration from ideal to practical use is typical of any real-life process. The FC was promoted from a laboratory curiosity to a vital function with the advent of manned space flight, which requires hydrogen and oxygen on-board for propulsion and life-support systems, making the FC particularly attractive for local power needs.

Compared to thermal machines, FCs have outstanding potential:

- Efficiencies are not limited by the Carnot one, and they increase with decreasing load; together these characteristics combine to give a doubled efficiency over a driving cycle.
- Increased flexibility in use, since the electrochemical reactions are practically instantaneous: in practice, fast startup and shutdown with low-temperature devices, and smooth load change with electrical drive.
- No pollution of a chemical or acoustical nature, except from the air blowers as presently used.
- The modular construction confers geometrical ease of adaptation to given volumes, and strong potential for capital cost reductions on scale-up to industrial production.

Compared to storage batteries, the FC has the great advantage of one to two orders of magnitude improvement in energy density (kWh/kg).

Despite these advantages, before FCs can be considered realistic for large-scale urban transport the following difficulties must be overcome:

- High capital cost, probably subject to steep economies of production, but saddled with precious catalysts both scarce and expensive.
- Low current densities at electrodes, increasing bulk and weight, decreasing useful load and decreasing vehicle efficiency at the wheels.
- Hydrogen storage.

Although these drawbacks make FCs impractical for industrial use today, the space applications (the Shuttle has three 12-kW FCs) and increasing transport demonstrations (see Tables 1 and 2) are putting them in better perspective: the potential economies of future mass production are undeniable, and Pt loadings at the electrodes have decreased by one to two orders of magnitude in the past 10 years; current densities are increasing rapidly, and have improved threefold in recent years; while hydrogen storage can be roughly half that of ICE vehicles with the same range, and significant progress is being made as discussed in Chapter 3.

If we compare this perspective with that of the ICE at a similar stage in its development--say 100 years ago--there is every reason to be optimistic about FC development, provided it receives the concentrated industrial attention that the ICE enjoyed. This being said, one item could halt the large-scale deployment of FCs: their use of strategic and scarce catalysts. If the relative loadings cannot be brought to acceptable levels, not only the price but ultimately the unavailability of the present favorites (Pt, Pd, etc.) could be decisive.

A3.2 Types of Fuel Cells

The main distinguishing feature of FCs is the type of electrolyte.

Ideally, the *electrolyte* should allow easy passage of the hydrogen ions without allowing electrons through. At the moderate temperatures preferred for transport applications, a strong acid or strong alkali solution is indicated and led to earlier choices of phosphoric acid or potassium hydroxide alkali as electrolytes. Known respectively as PA FC and A FC, they have found some limited application. However, the actual experience has not been favorable and they are being abandoned for what is becoming the almost unique choice: an acid-type in the form of a solid polymer known then as a SPE FC, but now increasingly called the PEM FC.

The solid polymer electrolyte of the PEM FC comes in very thin sheets (only a few tenths of a micron) and, although it must be kept humid, it is not subject to liquid loss. The sheets are under proprietary trademarks or patents, are very expensive considering the bulk plastics industry behind them, and are presently marketed by Asahi, Ballard, De Nora, Dow, DuPont and probably others. Since only these thin sheets and relative humidity paths separate the electrodes, the stacking density (cells/cm) is relatively high but a limit is posed by the electrode thickness which demands inversely-proportional catalyst loading. The current density (A/cm^2) of these sheets is relatively high, and appears to be increasing rapidly. The result is -and the evolution is strongly in favor of the PEM FC- that it provides power densities (W/kg) over 260, as compared to about 100 for PA FC or 65 for A FC, all at efficiencies of 50%-55%.

Nonaqueous electrolytes are also being developed for FCs, the most important being molten carbonates, which operate at 650°C, and solid oxides, which operate at 1000°C. The high temperatures encourage the electrochemical reactions, and catalysts can be dispensed with, but other problems can arise on road vehicles and, so far, no project has emerged. Considerable interest is shown in these high-temperature FCs for stationary power generation.

Attention will be restricted in the following to the PEM FC, but much will be applicable to others, especially the aqueous low-temperature ones.

A3.3 FC System Optimization

The optimization of an FC has to proceed hand-in-hand with the system that transfers the FC power to the road wheels safely, economically, and reliably, and of course provide the usual driver comforts and satisfaction with no adverse environmental impact.

The FC *stack* will consist of a number of cells to give a compact unit, easy to accommodate in the available spaces, yet not too big to discourage stack substitution if one or more cells develop problems. The number of stacks will depend on the power requirements, which depend not only on the type of vehicle and loads, but on the drive system, which can be FC-only (to meet all power demands) or FC in hybrid coupling with storage devices such as batteries (allowing FC power to be more than halved). Not surprisingly, many projects are choosing the hybrid route.

The literature reveals little about stack components and performance. Besides the membrane, which is the main proprietary item, the quantities and disposition of catalysts, the electrode characteristics, and so on are confidential--a good sign of competition. Some academic sources (Anand et al. 1994; Lamy and Leger 1994) have compared membrane performance in terms of voltage/current density, but developments underway can easily change the results. New suppliers are obviously entering the field, a trend which could well continue.

The *hydrogen supply* is another major system choice to be optimized with the fuel stack. If pure hydrogen is the choice, either as LH_2 or GH_2 or MH, it can be regarded as an independent variable with little influence on FC performance. Certainly it is less than for the ICE whose performance, as illustrated in Appendix 2, can be significantly influenced by cryogenic temperatures. The hydrogen storage, refilling, and safety questions are otherwise similar to ICE situations.

For whatever reason, more attention is being given to methanol as a hydrogen-rich storage medium with FCs than with ICEs. After reforming, which needs significant heat input (at least 15% of FC power), the hydrogen is fed to scrubbers where the CO and other impurities are removed; CO is particularly poisonous at the anode (<100 ppm and even as low as <10 ppm are required values quoted in the literature). Perhaps the high starting efficiency of FCs, or less likely the hope that direct reaction of methanol at the anode can take place (Lamy and Leger 1994 do not rule it out, although Höhlein et al. (1994) do, on the basis of its electrochemical activity about two orders of magnitude less than that of hydrogen), are the reasons for interest in methanol. Of course it is an easy-to-handle liquid, but if anything it is easier to use in ICEs than in FCs. In both cases it does little to mitigate global warming, unless the methanol is derived from biomass. In both cases its thermal inertia for startup, shutdown, and power change are negative features for road vehicles.

Turning to *oxygen supply*, it is taken for granted throughout the literature that air, i.e. an oxygen-rich, readily available gas, is the only choice for terrestrial applications. There are probably several reasons for this:

- Taking up yet more space and weight with LO_x is not an option.
- The safety questions of LO_x, especially its tendency to readily ignite any combustible substance.
- It adds considerable running costs.
- The nitrogen in air has no deleterious effect as it does in ICEs.
- The electrochemical reaction at the cathode with air, especially if a reasonable flow and pressure are maintained, is acceptable.

The penalty is that the air pressure must be raised and/or a steady flow maintained. Raising the partial pressure of oxygen by compressing the air is useful, but the parasitic load is not compensated by much improved FC efficiency (Chamberlin et al. 1994); more indicated is a low-pressure air blower, with the air flow matching power output. Present versions are reportedly noisy.

Anand (1994) gives some striking results of the reduction of cell voltage when air is used instead of oxygen at the cathode.

Turning finally to the *electrical transmission* system, the drive train draws on traditional technology even if a hybrid FC/energy storage device is used. Such a device, as already mentioned, allows the FC to be dimensioned for average steady load, leaving power peaks to the storage device, e.g., a battery that can be recharged at low loads and during regenerative braking. Other storage devices are possible, but not yet being used on any project on Table 1 or 2. DC drive motors match easily to the FC and battery outputs, but alternating current motors are cheaper and more rugged, and probably reverse to alternator mode more easily on regenerative braking.

The advantages of electrical drives over mechanical ones are well known:

- They have high torque and efficiency over the full speed range.
- The gearbox can be eliminated if high-speed motors become available.
- A separate drive motor on each wheel is feasible.
- Modern power electronics allow smooth operation and control.
- Regenerative braking is applicable.
- Noise levels are much reduced.

The 11th WHEC includes several papers of interest to this appendix, and relevant points are included in the main text. In particular, the following papers can be quoted and are summarized in Appendix 4: Rusanov (1996), Ekdunge (1996), Dönitz (1996), Cleghorn (1996), Mantegazza (1996), Barbir (1996), Wurster (1996), Schmidt (1996), Scherer (1996), Friedrich (1996), Bevers (1996), and Fischer (1996).

APPENDIX 4

SUMMARIES of PAPERS on HYDROGEN VEHICLES

This appendix includes a summary of the technology concerning hydrogen vehicles at:

- The beginning of the report, as comprehensively dealt with in DeLuchi (1989), "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost."
- The end of the report, as found in the Proceedings of the 11th World Hydrogen Energy Conference, June 1996.

These papers are referenced throughout the report, which is based on all available documents found in standard retrieval systems for the period 1989-1995. Additionally, relevant comments are included from 11th WHEC. However, other papers from 1996 were not consulted.

DeLuchi, M.A. (1989), "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," University of California, USA, *Int. J. Hydrogen Energy*, vol. 14, No. 2, pp. 81-130.

To do justice, however rough, to this long article, we can only follow its chapters, extracting what seem the most relevant points for present purposes. The summary is necessarily long, because each chapter of the 49-page article deals with a different aspect of the technology and economics of hydrogen vehicles, the only exceptions being the absence of GH_2 storage and fuel cells.

DeLuchi's own summary is far too short to be useful in the present context, but it sets the stage, and is therefore reproduced as follows:

Abstract - Hydrogen offers the prospect of plentiful supplies of clean transportation energy. This paper is a comprehensive review and analysis of hydrogen in efficient passenger vehicles. It addresses hydrogen production and distribution, on-board storage technology, refueling, vehicle performance and safety, the environmental impacts of hydrogen use, and life-cycle costs. The environmental impact analysis focuses on NO_x emissions from vehicles, the environmental impacts of making hydrogen from coal, and the contribution to the Greenhouse effect of CO_2 emissions from the use of coal-based hydrogen. The life-cycle cost model compares hydrogen vehicles to similar baseline gasoline vehicles, and includes estimates of the total retail cost of liquid and gaseous hydrogen from coal and solar-powered electrolysis, the cost of fuel storage equipment, the cost of pollution control equipment, maintenance costs, other ownership and operating costs, and the external costs of hydrogen use. While there is considerable uncertainty about several important parameters, I conclude that under certain plausible (though not necessarily likely) conditions -low hydrogen fuel and vehicle costs, high nonmarket costs of gasoline use, and moderately strong efforts to avoid a Greenhouse warming- hydrogen vehicles could be the preferred highway transportation option.

1. Introduction

Hydrogen is a very attractive transportation fuel in two important ways. It is the least polluting that can be used in an internal combustion engine, and it is potentially available anywhere there is water and a clean source of power.

....

The strongest hydrogen vehicle development efforts are in Japan and West Germany......
This paper is a comprehensive review and analysis of the use of hydrogen in road vehicles.

2. Hydrogen Production

The most abundant and accessible hydrogen-dense feedstocks are water, coal, oil and natural gas.

....

Of course, <u>fossil fuel hydrogen</u> is not a clean, renewable resource. Most of the hydrogen research community agrees that eventually hydrogen should be produced from water. Nevertheless it may be easiest to sustain a transition to hydrogen by expanding commercially-available, relatively inexpensive production processes, such as the manufacture of H_2 from coal for many decades, environmental considerations aside......

....

Hydrogen also can be produced from the gasification of biomass....

However the biomass resource base, although renewable, is many times smaller than the coal resource base.

....

For simplicity, this paper considers only the most abundant hydrogen feedstocks: coal to represent a low-cost base in the near-to-medium term, and solar water electrolysis as a low-environmental impact case in the longer term.

....

Water can be decomposed thermally at temperatures above 2500 K.....(but) many researchers do not think thermochemical production is very promising, and favor electrolytic and photolytic water-splitting techniques instead..... In my analysis, I consider water electrolysis only...

Non-fossil feedstocks should be used....of these, solar energy and nuclear energy are available in the long term.....; this cost analysis examines solar hydrogen.

3. <u>Hydrogen Distribution</u>

Typically, hydrogen would be transported from the site of production to end users as a gas, via pipeline. Ideally, the current natural gas system would be used for at least the initial stages of a transition to hydrogen. However, pure hydrogen reacts at the surface of certain pipeline steels, embrittling them and accelerating the growth of fatigue cracks.....(but) compounds can be added to hydrogen to inhibit embrittlement, (but) none is safe, inexpensive and effective. Otherwise, dedicated pipelines would have to be built.

....

Hydrogen also could be shipped in <u>liquid form</u>, in 49 000 l tank trucks, 132 000 l rail cars, or, for short distances, in vacuum-jacketed pipelines.

4. <u>Vehicular Fuel Storage and Refueling</u>

Hydrogen may be stored on board a vehicle as a gas bound with certain metals, as a liquid in cryogenic containers, or as highly compressed gas (690 bar) in ultra-high-pressure vessels. Other forms of hydrogen storage, such as glass microspheres, cryoadsorbents, and liquid hydrides, are discussed in the literature...

....

The metals most used in <u>hydrides</u> are iron, magnesium, nickel, manganese and titanium. Vehicular hydride storage systems are usually long thin hollow cylinders, tightly bundled, and pressurized with hydrogen to about 34 bar. When the vessel is charged, a good deal of heat is released... and during discharge the reaction is reversed and heat is required.

....

The most serious shortcoming of hydrides is their low mass and volumetric energy density...The low mass density of most hydrides means that hydride vehicles are much heavier and less efficient than comparable gasoline or LH_2 vehicles, and are limited by storage weight to about a 150-300 km range.

....

Hydrides are susceptible to contamination by impurities in the hydrogen gas.....(and) a 99.999% purity is necessary to insure that hydrides have relatively long lives.

....

Refueling hydride vehicles is relatively simple. It appears that hydride vehicles can be refueled in 10 min or less, although a wide range is given in the literature, and usually a good deal more time is needed to fill the last units of capacity.

....

A significant advantage of using liquid hydrogen is that LH_2 systems are much lighter and often more compact than hydride systems providing an equal range. Liquid hydrogen storage is not significantly heavier than gasoline storage, on an equal-range basis; it is however much bulkier.

....

Thus an advanced LH_2 tank probably would weigh only 10 kg more than a full gasoline tank.......(but) complete LH_2 systems are about 6-8 times larger than gasoline tanks holding the same amount of energy. However the LH_2 will go up to 50% farther on the same amount of energy, so that, on an equal-distance basis, LH_2 systems will be 5-6 times larger.

....

A safely-run, easy-to-use, public LH_2 refueling station is probably within the scope of current technology and practices.

....

Beginning in 1979 LANL operated a LH_2 vehicle and refueling station for 17 months; the results indicated that fast and safe LH_2 self-service was possible. The LH_2 vehicle was refilled in less than 10 min when the tank was cold. In 1982 Peschka remarked that an LH_2-powered BMW was refueled "without any major difficulties" also in under 10 min when the tank was cold.

....

A simple way to store hydrogen on board is as a compressed gas in high-pressure vessels.... (For) a more manageable volume the pressure must approach 690 bar. Lightweight carbon-wrapped aluminum cylinders capable of storing hydrogen safely at this pressure are available, but heretofore have been used in aerospace applications, and would be very expensive for vehicular use.......At 690 bar, a carbon/aluminum storage vessel providing a 420 km range would be about three times heavier and nine times larger than the gasoline tank.......

....

Hydrogen can be stored in glass microcapsules at high pressure. This system is comparatively simple and has the potential to be relatively lightweight and inexpensive.....(but) is not nearly as advanced as hydride research........

....

A liquid-hydride based system for trucks and buses has been developed... (but) thus far the cost, bulk and weight of the total system appear to limit it to heavy-duty vehicles......

5. Performance of Hydrogen Vehicles

The overall fuel efficiency of a hydrogen vehicle, relative to a comparable gasoline vehicle, is a function of the difference in weight , and the difference in thermal efficiency. The weight differences are due to pollution control equipment, fuel storage systems, and engine components. A 1% increase in vehicle weight causes about 0.8% decrease in overall efficiency.

Hydrogen can be considerably more thermally efficient than gasoline, primarily because it runs better in excess air, and permits the use of a higher compression ratio.... Data from engine tests indicate that hydrogen combustion is 15 to 50 % more thermally efficient.. Some claim as much as 100 % with ultra-lean operation. The actual value depends on the air-fuel ratio, how well the engine is optimized for hydrogen combustion, whether GH_2 or LH_2 is used, the fuel injection scheme, and other factors. For example, late injection of LH_2 offers the potential of higher efficiency by reducing the pressure rise in the cylinder, and reducing thermal losses through the cylinder walls.

In general, engine power..... is proportional to the volumetric heating value of the air-fuel mixture. The greater the charge density, the greater the power. At near-ambient temperatures, gaseous hydrogen displaces much more air in the combustion chamber than does atomized gasoline, and thus reduces the density of the fuel charge. If the air/fuel mixture is stoichiometric (ideal), and near ambient temperature, the power loss, theoretically is around 30 %.

This loss can be reduced or eliminated by using cryogenic fuel. In fact , if LH_2 is injected into the chamber, after the intake valve has closed, near top dead center, and thus at high pressure, there is actually a 17 % increase in power at stoichiometric, relative to the gasoline case at stoichiometric.....
It appears there have not been any engine tests with ultra-high pressure GH_2...

There is a tradeoff between power and efficiency and NO_x emissions: very lean operation increases efficiency and reduces NO_x but also reduces the volumetric heating value of the air/fuel mixture (because there is less fuel) and thus reduces power....

It is not possible to specify universally optimal operating parameters for hydrogen engines, since individuals and regulators place different values on power, fuel cost (efficiency) and NO_x emissions. Nevertheless, a satisfactory balance of these parameters likely could be found in most situations, at least with LH_2. For example, a hydrogen engine operated at an equivalence ratio of around 0.6 would be considerably more efficient than a gasoline engine at 0.9, produce much less NO_x and, with internal mixture formation of pressurized, cold LH_2 and turbocharging, could offer as much power as the gasoline engine.

Late direct injection of cryogenic hydrogen increases power output and efficiency... It eliminates preignition and backfiring and reduces NO_x formation. For these reasons, many hydrogen researchers feel that it is the most desirable form of hydrogen injection.

However, the technical demands of this method are very exacting. Hydrogen is injected about 5^o before top dead center, when the pressure of the burning gases is high, and so the hydrogen must be pressurized by a pump. If the pump is outside the LH_2 tank and draws off boiling LH_2, it is subject to cavitation. If it is immersed in the LH_2 tank this problem is eliminated, but heat flows into the tank along the pump, and from the action of the pump, accelerate boiloff. The hydrogen injectors must be able to stand a wide range of temperatures and operate at very high rpm. A high-swirl combustion chamber and precise fuel injection are needed to insure a homogeneous air/fuel mixture in the very short time between injection and combustion. Work on these technical problems has just got underway, and there is no reason to suppose that they are insurmountable.

Perhaps more importantly, direct late injection of cryogenic, pressurized fuel requires on-board storage of LH_2 fuel. If safe disposal of boiloff gases is not possible, widespread acceptance of LH_2 vehicles .....is unlikely.

To date, hydrogen performance data have been gleaned from modified, stock gasoline ICEs. It is important to recognize that test vehicle engines have not been completely optimized for hydrogen combustion, and that the ICE may not be best for hydrogen. The results so far are probably only suggestive of what can be achieved with a dedicated hydrogen engine.

Regarding preignition and backfiring, hydrogen ignites at an order-of-magnitude lower temperature than does gasoline, and as a consequence, hot oil, hot metal in the combustion chamber, or the kinetic energy of the residual gases, under some conditions, cause preignition of the air/fuel mixture and backfiring into the intake manifold.... To avoid this, the combustion environment hot spots must be cooler than the minimum ignition temperature of hydrogen. Several methods of avoiding backfire are; inject cooled exhaust gases into cylinder; inject water into cylinder; use cold GH_2; inject GH_2 or LH_2 late in compression stroke; use lean-burn carburetor; use special oils and materials; increase compression ratio.

....

Regarding engine wear the available data and theory do not permit a definite conclusion, but suggest that hydrogen engines may have lower oil costs and very slightly lower maintenance costs than gasoline engines.

Generally, dual-fuel (H_2/gasoline) vehicles and engines are more efficient and have lower emissions than stock gasoline ones.....

6. Safety Issues

Hydrogen has a largely undeserved reputation as a particularly dangerous fuel.

....

Hydrogen is more hazardous than gasoline in several ways. Like methane, it is invisible and odorless, and therefore an odorant must be added to enable detection. Hydrogen flames are very hot, yet radiate very little heat and are invisible, which makes them harder to locate, and thus harder to extinguish or to avoid. A flame colorant would make detection easier. (Odorants and colorants must not contaminate hydrides). Hydrogen can ignite within a rather large range of hydrogen/air densities, from 4 to 74 % (by volume), and compared to methane or gasoline needs very little energy to ignite. However, the lower volumetric ignition limits for CH_4 and H_2 are close, and in a weak ignition source such as an electrostatic spark, there is already sufficient energy to ignite CH_4. Thus in practice, H_2 may not be much more prone to ignition than CH_4.

Hydrogen has a much higher normal burning velocity than has methane or propane. This means that, given a burning, detonable mixture of hydrogen, methane or propane in a confined space, the hydrogen conflagration is more likely to detonate. However, if the mixture is not burning, is not capable of exploding or is not in a confined space, this is no longer true. Thus hydrogen is more explosive than the other fuels only in certain circumstances.

Contact with LH_2 destroys human tissue. Wearing gloves reduces the risk.

On a volume-of-gas basis, hydrogen has a lower explosion potential than either methane or propane; on a mass-of-fuel basis, hydrogen has the most explosion potential; but volume considerations are more pertinent to storage safety.

Hydrogen fires burn very rapidly, and radiate very little heat, and thus are relatively short lived.... a person can be closer to a H_2 fire than a gasoline fire without being burned.

...in a test crash of an LH_2 vehicle the fuel system remained intact....similar outcomes of on-road crashes of demonstration vehicles. LH_2 tanks seem less likely than jet fuel tanks to explode when struck by lightning or punctured...this probably applies to LH_2 dewars vs gasoline tanks as well. If LH_2 does leak in a crash, it will evaporate and disperse exceedingly fast, unlike gasoline which will puddle and remain a fire hazard for much, much longer.

It has been shown that hydrides are safer than gasoline tanks. Unless a continuous supply of heat is available to desorb the hydrogen, a leak from a hydride tank will be self-limiting.

LH_2 refueling is expected to be automatic, fast and safe. Hydride refueling also presents no unusual hazards....

....

Current technology LH_2 vehicles vent at 3-5 bar which is reached after 2-5 days. If boiloff control proves to be feasible and relatively inexpensive, then the market potential of LH_2 vehicles will not be limited by safety concerns related to boiloff.

....

Assuming that advanced technology tanks will have a lock-up time of 4 days, and a boiloff rate of 1.3% per day, a vehicle that remained idle for a week would lose less than 5% of its fuel. This likely would not be noticed....

7. Environmental Impacts of Hydrogen Vehicles

The great attraction of hydrogen is pollution-free combustion...... Hydrogen vehicles would not produce, either directly or indirectly, significant amounts of CO, HCs, particulates, SO_x, sulfur-acid deposition, ozone and other oxidants, benzene and other carcinogenic aromatic compounds, formaldehyde and other aldehydes, lead and other toxic metals, smoke, or CO_2 and other Greenhouse gases. The only pollutant of concern would be NO_x. If hydrogen is made from water using a clean power source, then hydrogen production and distribution will be pollution-free. Hydrogen thus is a truly clean fuel.

In this section, the environmental impacts of hydrogen production, distribution and end-use are reviewed with particular emphasis on the environmental impacts of using coal as a feedstock for hydrogen, NO_x emissions from vehicles, and the Greenhouse effect of substituting hydrogen for gasoline and diesel fuel.

Concerning hydrogen production and distribution, ..using clean solar power or other forms of renewable energy is essentially pollution-free.

The manufacture of some solar energy-converting technologies produces small amounts of undesirable by-products....

Although solar-hydrogen plants are likely to be land-intensive, land requirements per se are not likely to be an important restriction on the development of solar hydrogen production.

....

The use of coal to produce hydrogen would not be a desirable long-term option from an environmental standpoint: first, coal mining is environmentally damaging and dangerous; second, emissions from coal-to-hydrogen plants may be significant and harmful; third, and most importantly, the use of coal inevitably releases large amounts of CO_2 and other trace Greenhouse gases.

....

Concerning vehicular emissions, NO_x is the only significant pollutant from hydrogen vehicles....(and) is undesirable for several reasons. First, it can cause acute and perhaps long-term respiratory ailments. Second, reactive hydrocarbons and NO_x are involved in a complex series of chemical reactions that form ozone, a potent oxidant that damages plants and materials and also causes respiratory problems. Third, emissions of NO_x form particulate nitrates, which reduce atmospheric visibility and, again, may have serious respiratory effects. Nitrates are the principal constituent of acid deposition in the Western U.S. Finally, NO_x forms other toxic, mutagenic and carcinogenic compounds......

Formation of NO_x in any internal combustion engine is primarily a function of reaction temperature, and duration and available oxygen. Emissions of NO_x increase with the combustion temperature, the length of the high-temperature combustion period, and the availability of oxygen, up to a point. There are several ways to control NO_x in a hydrogen engine: run the engine very lean, which lowers the temperature, or very rich, which reduces the oxygen supply; decrease the burn time or lower the engine rpm (which allows for better heat dissipation); or cool the combustion environment by adding water or exhaust gases or using cryogenic fuel.

From the (available) data, and theoretical discussions, several conclusions can be drawn:

- optimized hydrogen vehicles can emit much less NO_x than do comparable, optimized gasoline vehicles;
- an optimized hydrogen vehicle could meet the current US NO_x standard, and perhaps have lower lifetime average NO_x emissions than a current-model catalyst-equipped gasoline vehicle, without after-treatment of the exhaust gas;
- the NO_x emissions deterioration rate probably would be lower for hydrogen vehicles than for gasoline vehicles;

- HC and CO emissions from hydrogen vehicles with no after-treatment of exhaust gas are about an order of magnitude lower than HC and CO emissions from catalyst-equipped gasoline vehicles of similar age and engine condition;
- CO_2 emissions will be lowered by two or more orders of magnitude, depending on the oil consumption of the engine;
- hydrogen vehicles would emit or produce close to zero ozone, particulates, sulfates, sulfur oxides, aldehydes, benzene, and other toxic and carcinogenic compounds commonly found in the exhaust of petroleum-fuel vehicles;
- dual-fuel operation with hydrogen and gasoline or diesel fuel can substantially reduce emissions of all regulated pollutants.

....

It (also) appears that LH_2 vehicles may be quieter that gasoline vehicles, and hydride vehicles louder, but it is not known if this difference is important.

Concerning <u>hydrogen vehicles and the Greenhouse effect</u>, the use of hydrogen made from non-fossil electricity and water is one of the most effective ways to reduce anthropogenic emissions of Greenhouse gases.

....

On the other hand, the use of coal to make hydrogen would cause a substantial increase in emissions (per km) of Greenhouse gases....(up to) 100 % (hydride vehicles) and 143 % (LH_2 vehicles) with respect to current emissions of Greenhouse gases from petroleum use.

Ironically, it thus turns out that hydrogen is either the best or the worst fuel from a Greenhouse perspective, depending on the feedstock...... Hydrogen from non-fossil power, or a combination of electric vehicles and ICE vehicles using biofuels, would be the only effective long-term options for eliminating emissions of Greenhouse gases from transportation sector.

....

Much more water vapor is formed by hydrogen combustion than by the burning of fossil fuels. Moreover, water vapor is actually the most important Greenhouse gas in the atmosphere, controlling many times more infrared flux than CO_2. However, even if hydrogen replaced all fossil fuels world-wide, the increase in water vapor emissions would amount to only 0.003 % of global evaporation. This is a negligible amount... (but) some monitoring over the long term might be prudent, since small changes in water vapor or cloud cover can significantly affect climate.

8. Liquid Hydrogen and Hydride Vehicle Life-Cycle Cost[1]

8.1 Assumptions

Cost estimates for mass-produced carbon/aluminum vessels for vehicular use are not available. Therefore, life-cycle costs are estimated for LH_2 and hydride vehicles only.

....

Hydrogen's environmental advantages are generally thought to be outweighed by the very high cost of hydrogen fuel and hydrogen vehicles.....
The purpose of this section is to quantify as precisely as the data permit the life-cycle cost difference between gasoline and hydrogen vehicles.

....

The life-cycle cost per km is the sum of the fuel cost per km, the amortized vehicle initial price, and other per-km operating costs. The fuel cost per km is a function of fuel price and vehicle efficiency; the fuel price is the sum of hydrogen production and delivery costs, retail station cost and fuel taxes. The amortized initial price includes the price of the basic vehicle (identical for hydrogen and gasoline) plus differences between the hydrogen and gasoline vehicle in the cost of underhood components, pollution control equipment and on-board fuel storage equipment. Other operating costs include maintenance costs, tire replacement cost (a function of vehicle weight), insurance and registration cost (a function of vehicle initial costs), and external costs.

All cost figures are in 1985\$, unless specifically otherwise stated. The GNP implicit price deflators were used to convert to 1985\$.

The baseline gasoline vehicle, ...(specified in detail)....is assumed to weigh 1150 kg and do 14.88 km per l.

....

The standard U.S. FHWA estimates were used for maintenance costs, parking and tolls, accessory cost and oil cost. In the base case it is assumed that the purchase of the car is financed at a real rate of 9% per year.

....

..assumed that vehicle range is relatively important up to about 400 km, and relatively unimportant above. Thus the choice of 420 km for the LH_2 vehicle. Hydride vehicles are additionally limited in range by the weight of the storage system: 210 km is assumed.

The summary cost statistic used in this analysis is the break-even gasoline price........that retail price of gasoline in \$ per l including current total average fuel taxes in the U.S. (\$0.053 per l), which equates the total cost per km of the gasoline vehicle and the total cost per km of the hydrogen vehicle. The break-even price is calculated on both a social cost basis and private cost basis. The social cost basis includes very rough estimates of external costs, such as economic damages from air pollution and the macroeconomic costs of importing oil. The break-even gasoline price can be compared with the current price to determine, intuitively, how close hydrogen vehicles are to being economically competitive.

A best case for the hydrogen vehicle is also estimated. This is the break-even price of gasoline given the high external cost estimate for the hydrogen and the gasoline vehicles and the low private cost estimate for the hydrogen vehicle.

Costs are estimated for the near-term, through the year 2010 or 2020, in which case hydrogen is assumed to

[1] This section is by far the longest in the Article, and this summary cannot do it justice even though the sub-division into 10 sub-chapters has been followed; accent is placed on the methodology and results, and not on the input data which probably need updating to be of present significance.

be made from coal, and for the middle-term (the years beyond), in which hydrogen is assumed to be made by water electrolysis using solar power. Both these scenarios assume mass production and advanced technology, but no major technical breakthroughs. Uncertainty in cost projections is handled by using high and low cost estimates; the lower bounds represent very optimistic assessments of what is attainable in the future, and the higher bounds relatively pessimistic assessments. In the near-term scenario, hydrogen is assumed to satisfy on the order of 10-20% of the demand for highway transportation fuels. Fuel prices are estimated for this level of demand and are meant to give an idea of the relative costs of the hydrogen in the early stages of a full national transition. In the middle-term scenario, hydrogen is assumed to command the majority of the highway fuels market, and prices are assumed to be indicative of relatively stable long-term prices, after a complete transition.

8.2 The cost of hydrogen production

In the near-term scenario, the cost of producing <u>hydrogen from coal</u> depends on the gasification technology, the cost of the feedstock, the size of the plant, among other things.

....

All this considered, it is likely that the market-clearing plant-gate price of hydrogen from large, advanced coal-based plants in the near-term, would be between \$7 and \$13 per million Btu (mmBtu).

The cost of <u>solar hydrogen</u> depends on the non-energy costs of electrolysis, the electricity cost at the site of generation, and the overall efficiency of electrolysis.

....

(After analysis of considerable input data) the non-energy cost of electrolysis is taken as \$7-12 per mmBtu, and the overall efficiency of electrolysis as 75-90% for large advanced systems. No credit is taken for the sale of byproduct oxygen nor for the use of electrolysis waste heat........ There is a good deal of uncertainty in projections of the cost of solar power....The best estimates for advanced post-2000 PV or solar thermal technology indicate an electricity production cost of not less than \$15-20 mmBtu, and not more than \$50 per mmBtu. A range of \$18-45 is taken.

8.3 The cost of hydrogen transmission and distribution in pipeline

...the largest components of total hydrogen transmission cost are the capital costs of the compressor stations and the pipeline and the cost of the fuel (pipeline gas) used by the compressors. Transmission cost is also a function of pipeline diameter, shipping distance and working pressure. Hydrogen compressors must be about 35% closer together and have 3.8 times more capacity, and 5.5 times more horsepower than CH_4 compressors, in order to ship the same amount of energy, mainly because H_2 is about one-third as energy dense as CH_4 on a volume basis. The larger H_2 compressors are more expensive, and the hydrogen energy they use is more costly per energy unit than CH_4.

....

Normalized to a hydrogen production cost of about \$7-13 per mmBtu for the near term, and \$10-45 for the middle term, a shipping distance of 1600 km, and a flow rate of 10^{10} Btu per hour, a national average transmission cost of \$3-6 per mmBtu for delivery of solar H_2 to retail stations, and \$2.50-5.00 to industrial liquefiers, result from various estimates. For fossil H_2 the corresponding figures are assumed to be \$2-4 and \$1.50-3.25.

8.4 The cost of liquefying hydrogen

The cost of liquefaction depends on the cost of delivered electricity ($14.65-16.41 per mmBtu in near term, 3.50-5 for transmission plus 18-45 for solar power in middle term), the efficiency of liquefaction (26-33%), and the non-energy cost of liquefaction ($2-4 per mmBtu).

....

(Some doubt for the present writer surrounds these summary figures, and DeLuchi does not quote explicitly in his text the resulting cost of liquefaction; a Table however gives the liquefaction cost as $9.42(high)-5.81(low) per mmBtu in near-term, and $20.50(high)-7.59(low) in middle-term.)

8.5 Refueling station cost and fuel taxes

A hydride refueling station is assumed to serve 200 vehicles per day over 18 hours, and each vehicle (210 km range) withdraws 82% of its full 0.426 mmBtu capacity. Pipeline hydrogen would probably have to be purified at the station before delivery to vehicles (hydrides require >99.995% purity). Allowing for the costs of compression to 200 bar and of personnel, the total hydride station mark-up would be $3-4 per mmBtu. LH_2 refueling station costs are the sum of delivery and retailing costs. Truck delivery of LH_2 to most metropolitan areas is taken as $0.50-1.50 per mmBtu, and boiloff reduces the amount transferred at each step to 87-92%.....Taking known costs of LNG refueling stations with appropriate corrections, an LH_2 station cost of $4-5 per mmBtu is reached.

Regarding state and federal taxes, it is assumed that the tax-per-km would be 100% of the gasoline one in the near term, and anywhere from 50 to 100% of the gasoline one in the medium term.

8.6 The effect of thermal efficiency, vehicle weight and pollution control equipment on vehicle life-cycle cost

These three items directly affect the km per mmBtu of both hydrogen and gasoline vehicles. ....It is assumed that most H_2 vehicles would be run fairly lean, with 20-45% more thermal efficiency for LH_2, and 20-42% for hydride vehicles.....A typical, full, advanced LH_2 tank would weigh about 10 kg more than the full gasoline tank it would replace, in 420-km range vehicles, and would be compensated by the pollution control equipment not needed. The extra weight of the hydride vehicle would be 200-260 kg compared to the gasoline vehicle. Pollution control equipment on the gasoline vehicle can be ignored, as far as weight effects are concerned, as various factors balance out.

8.7 The price of the vehicle

Concerning engine equipment it can be assumed that both hydride and LH_2 engines would be about $50-200 more expensive than a comparable gasoline engine, allowing for fuel induction, injection and backfire control in the former.

Concerning engine size, advanced LH_2 engines will be at least as powerful as gasoline engines of similar size....And since LH_2 vehicles will not be heavier, it is assumed that there is no cost difference due to engine size between an optimized LH_2 engine and a gasoline engine providing the same performance.

....

Rather than attempt to estimate the additional cost of bringing the performance of the hydride vehicle up to the level of the gasoline vehicle, assume no cost difference, and note that performance would not be comparable.

Concerning pollution control equipment , hydrogen vehicles would not require a 3-way catalytic converter, start-up catalyst, oxidation catalyst, oxygen sensor, evaporative emission control, air injection, exhaust gas temperature sensor, and more....In spite of higher figures advanced by the automotive industry, the cost of pollution control equipment on gasoline vehicles, and the consequent price reduction for hydrogen vehicles, probably would not exceed $300-400.

Concerning maintenance cost of pollution control equipment, it seems reasonable to assume that the present value (10% discount rate) of foregone emission control maintenance costs would be at least $50, bringing the $300-400 just mentioned to $350-450.

Concerning vehicle life, hydrogen shares with natural gas some of the properties that purportedly give the latter its life-extending benefits, so, given a gasoline vehicle life of 210 000 km, 193 000-240 000 km is assumed for hydrogen vehicles.

The incremental initial cost of hydride storage is subject to many uncertainties, but a cost range of $1500-2400 is assumed here for an advanced, mass-produced, complete hydride system...suitable for vehicular use. Concerning hydride life and salvage value, it is assumed that hydrides could have a very high salvage value at the end of the life of the vehicle - perhaps as much as 50% of the initial cost. - but only 15% is taken... Concerning incremental cost of LH_2 storage, there are few, recent estimates of the cost of mass-produced, advanced LH_2 tanks.....Using them however, it is assumed mass-produced, advanced, 80-100 l tanks, with fuel delivery and boiloff control would add $700-1700 to the price of the car..... In the absence of good data, it is assumed that Dewars would have a salvage value of 10-25% of their initial cost, at the end of the life of the vehicle.

8.8 Vehicle maintenance, operating and other periodic costs

...balancing various factors, it is assumed that yearly maintenance costs with respect to the gasoline vehicle base case would be 90-110% for the hydride vehicle and 90-105% for the LH_2 vehicle, and that hydrogen vehicles would have 50-90% of the yearly engine oil replacement cost of gasoline vehicles.

In the cost program, the life of the tires on the hydride vehicle is equal to baseline tire life for the gasoline vehicle divided by the ratio of the weight of the hydride vehicle to the weight of the baseline gasoline vehicle.

...the baseline gasoline vehicle registration cost...is multiplied by the ratio of the initial cost of the hydrogen vehicle to the initial cost of the gasoline vehicle.

...it is assumed in the low-cost scenario that insurance payments would be the same as for the gasoline vehicle,.....but....that insurance payments would be about 8% higher for LH_2 and 12% for hydride vehicles in the high-cost case.

Finally, fuel lost to boiloff must be treated as an economic loss. In the low-cost case, it is assumed that the vehicle is driven frequently enough to prevent any boiloff, and in the upper-bound case.....would be 10% of the fuel.

8.9 External costs of hydrogen vehicles

The use of hydrogen from coal, and to a much lesser extent solar hydrogen, imposes several kinds of costs on society which are not borne by those who pay for the vehicle and the fuel.

....

The analysis is based on a 1987 DeLuchi report as updated to 1989.

For the gasoline vehicle base case, the external cost consists primarily of air pollution damages and the macroeconomic costs of importing oil; it does not include the “costs” of a Greenhouse warming or of military tensions and conflict related to importing oil; the result is \$0.89-19.09 per mmBtu for vehicles with catalytic converters.

For the coal-based hydrogen case, the external costs are due to: accidents and land damage of coal mining and transport (\$0.16 per mmBtu of coal mined); pollution from coal-to-hydrogen plants (\$0.12-1.39 per mmBtu of coal input); pollution from electricity consumption, particularly in the near-term scenario , and for hydrogen liquefaction (\$2.02-43.65 per mmBtu of end use); LH_2 truck increased accidents -5 times as many corresponding gasoline truck deliveries- and insurance, agency outlay, subsidies, NO_x pollution,...are further minor cost items considered for hydrogen vehicles.

The overall results in \$ per mmBtu of fuel purchased for passenger vehicles are:

- 0.70-6.72 for near-term hydride
- 2.30-30.82 for near-term LH_2
- 0.20-2.73 for middle-term hydride
- 0.29-4.22 for middle-term LH_2

and can be compared to that for gasoline vehicles just quoted:

0.89-19.09.

....

(Obviously), hydrogen vehicles based on coal (i.e. near-term), especially when electricity-intensive LH_2.is used,......would not be environmentally desirable.

8.10 Discussion of cost results

It is worthwhile summarizing the break-even gasoline price in the various scenarios, with federal and average state tax in the US, (reproducing here DeLuchi's Table 26):

		Best Case		Social Cost	Private Cost
	Near-Term		High	1.71	1.41
LH_2		0.42	Low	0.45	0.42
	Middle-Term		High	3.08	3.58
		0.41	Low	0.90	0.92
	Near-Term		High	0.78	1.20
Hydride		-0.02	Low	0.38	0.39
	Middle-Term		High	2.64	3.18
		0.38	Low	0.90	0.92

(While stressing their indicative, uncertain character, DeLuchi draws some interesting conclusions):

- in all high cost cases, hydrogen vehicles are prohibitively expensive, even if external costs are included;
- external costs do not make a difference qualitatively in most cases;......this indicates that uncertainty regarding the private cost of hydrogen vehicles, rather than consideration of external costs, dominates most cost scenarios;

- the best cases however, hydrogen vehicles approach competitiveness, since middle term gasoline prices of \$0.40 per liter are not unimaginable, even in the U.S.; the hydride case of better-than-free gasoline suffers from the assumed 210 km range, and from much less power than with gasoline;
- the great range in breakeven prices is attributable primarily to the uncertain cost-per-km of hydrogen fuel in the middle term, due to uncertain price for solar electricity...;
- at lower interest rates, and higher baseline vehicle costs, hydrogen vehicles ...may be significantly more competitive than represented here;

9. Vehicle comparisons

....if a safe method of disposing of vents from LH_2 tanks is developed, hydride vehicles will lose most of their advantage.......since most of the breakeven gasoline prices for hydride and LH_2 vehicles are similar.

.....10-15 years research on hydrides has failed to produce the ideal candidate, which reinforces the notion that more serious attention be given to LH_2 vehicles....

....if a compressed gas H_2 (he goes for 690 bar) vehicle could provide the range of an LH_2 vehicle at the same cost, it could be the preferred hydrogen storage method.

.....costs aside, hydride vehicles would be inferior to gasoline vehicles in range, bulky storage, and performance...while LH_2 vehicles have the boiloff problem, and bulkier storage than gasoline vehicles

10. Areas for further research

Concerning fuel storage, three areas are emphasized for progress: hydrides for higher vehicle range and performance; "clever" repackaging of components to offset the inevitable loss of trunk space to bulky storage; reliable, low-cost boiloff control devices for LH_2 vehicles.

The possibility of small-scale H_2 liquefiers for refueling stations should be investigated.....
Concerning safety, perhaps the most important research issue is to determine under what conditions hydrogen can be shipped in the existing natural gas network.

Concerning performance and environmental impacts, ...it would be worthwhile to investigate the use of late injection of high pressure gaseous H_2 on volumetric density, and also on NO_x with lean operation (same for LH_2).

Concerning cost, the objective is defined as the best-case described in the paper, because in any other scenario hydrogen vehicles are not socially cost-effective, and in the worst cases they are extraordinarily expensive. If however, a relatively high value is placed on avoiding greenhouse warming and reducing dependence on an insecure and diminishing resource, this would change.

In conclusion, this paper does not support the notion common among policy makers that hydrogen vehicles are strictly an exotic, distant-future possibility.....With a strong R&D effort, normal technological progress, and the expected reduction in the price of solar electricity, hydrogen vehicles could be (socially) cost-competitive within 30 years or less.

Proceedings of the 11th World Hydrogen Energy Conference, June 1996 (Hydrogen Energy Progress XI), International Association for Hydrogen Energy in Three Volumes, 2,766 pages.

These proceedings contain 134 papers and 186 posters, organized in six topics; 37 papers and one poster from five topics contain information of direct relevance to the technological status of hydrogen road vehicles, and such information--or at least that part new to us--is summarized below. As mentioned in the Introduction, the text (which was prepared before the 11th WHEC) is now enriched by this new information.

Some papers, especially those of a keynote or overview nature, are omitted unless they contain new information that was not available when the original report was prepared (October 1995-May 1996).

TOPIC 1: Transition to Hydrogen-Based Energy Systems

Rusanov, V.D., *"Hydrogen Energy and Technologies: R&D in Russia*," Kurchatov Institute, Moscow, Russia pp. 37-48.

A concept of a city bus fueled with 300-350 bar GH_2 with 20 kW PEM FC is mentioned. The Russian Nafion-like membrane MF-4SK provides current densities as much as 1 A/cm^2 at <100ºC working temperature, and costs several times less than Nafion.

Ekdunge, P.; M. Råberg, "The fuel cell vehicle--analysis of energy use, emissions and cost," Volvo, Göteborg, Sweden pp. 93-101.

This paper examines a five-passenger car equipped with a PEM FC and compares it to a standard 93-kW Otto engine.

The challenge is to develop a cleaner, more energy-efficient vehicle, in order to further reduce toxic emissions and CO_2. The environmental perspective required is not only local but global, and must encompass the total life cycle of the product and the energy carrier, and pay due attention to costs.

A fast impact on the environment can be achieved only by further improvement of the ICE, with tailpipe treatment; if zero emissions are required, only the electric vehicle is presently available.

For long-term sustainability, and security of fuel supply, we need renewable fuels such as alcohols and hydrogen. (At this point the paper discards the ICE for H_2 vehicles, and opts for the FC as prime mover.)

On-board H_2 can come from off-board reforming of hydrocarbons; gasification of hydrocarbons, including coal, waste, biomass; water electrolysis; small local reforming of methanol or hydrocarbons; on-board methanol reformer.

Two versions of the same Volvo 850 car were simulated: a regular 93-kW Otto motor, and a 75-kW FC with a 41-kW buffer battery (Ni-hydride, 3 kg/kW) driving an electric motor whose 80% efficiency gives the same 93 kW at wheels.

The results are:

- Overall car weights: ICE 1,450 kg; FC 1,820 kg with either methanol or H_2 on board
- FC stack costs $1,220/kW, of which membrane 120 and catalyst $243/kW.
- Fuel consumption: FC/H_2 only 65% of ICE; FC/methanol as high as 91% of ICE; in future these figures can drop to 40% and 53% respectively, again for present ICE
- Global energy consumption of whole product and energy carrier life cycle: the present ICE and the present

FC/local methanol combination are the best; electrolytic hydrogen is worse by a factor of 2
- Global emissions are given for the unusual Swedish energy mix of 95% non-fossil (nuclear plus hydro), 5% hydrocarbons.

A future FC/composite material family car could weigh only about 800 kg, and the FC could decrease to 40 kW with 15 kW storage, giving the future energy consumption figures quoted above. The car performance would be similar to today's, but consuming only 3 liters of gasoline equivalent per 100 km.
The very high FC costs today (>$5,000/kW total of which >1200 for materials) must be reduced dramatically, and a figure as low as $49/kW for materials is advanced.

Schock, R.N., et al., "The Transition to hydrogen as a transportation fuel: Cost and infrastructure requirements," Lawrence Livermore N.L., California, USA, pp. 115-122.

The 188 million cars and trucks in the United States were responsible in 1991 for 29% of NO_x, 22% of HC, and 58% of CO emissions. Hybrid-electric hydrogen vehicles can today give a 250%-300% increase in fuel economy.

They propose a highly efficient 30-kW ICE (or PEM FC) in hybrid combination with a 2-kWh storage feeding a 40-kW average electric motor driving a 1,140-kg (empty) car able to accelerate from 0 to 96 km/h in <10 s, using the 100-kW peak power capability. The ICE runs at constant speed at maximum efficiency (45%) point.

A 3.75 kg H_2 storage would be enough for 480 km range, giving a gasoline-equivalent performance of 34 km/l. The H_2 storage system is regarded as the major challenge. The overall vehicle efficiency would be 40% compared to 13% for conventional vehicles in the urban driving cycle.

Various H_2 distribution systems are examined, and are estimated to lie around $2.50/kg of delivered H_2, permitting fleet fuel costs of <$0.03/km-vehicle, typical of today's conventional automobiles.

Fulton, J.; F. Lynch, "Leveraged use of hydrogen in internal combustion engines," Hydrogen Consultants, Colorado, USA, pp. 123-132.

The authors propose to use H_2 in combination with conventional fuels in transport applications, where the leverage effect of H_2 far exceeds its value as a 100% alternative fuel. Its value in the marketplace thus increases, awaiting the day when hydrogen's competitive disadvantage with conventional fuels no longer applies.

Examples of leverage are:

- Lean-burn operation, which produces less NO_x or CO, becomes much more feasible with H_2 (lambda=5) than with HC fuel (lambda<1.7)
- H_2 hybrid electric vehicles, where the constant conditions give a 90% reduction in NO_x compared to an ICE
- H_2 addition to natural gas, giving emission reductions proportionately greater than the H_2 addition, again by amplifying the clean-burn properties of both
- H_2 cold start to avoid the serious emissions of conventional fuel engines waiting for the catalyzer to warm up.

Moore, R.B.; V. Raman, "Hydrogen infrastructure for fuel cell transportation," Air Products and Chemicals, Pennsylvania, USA, pp. 133-142.

More than 8.5 million tonnes of H_2 are produced in the United States each year, but more than 95% is used in-situ to refine oil or produce commodity chemicals such as ammonia and methanol.

The remaining "merchant" H_2 is used in the chemicals, metals, glass, and electronics industries. Only a tiny fraction is used for transport, above all for the space program, and the LH_2 production capacity is 80 tonnes/yr distributed in 20,000 trailer loads /yr.

The paper examines the infrastructure options to supply fueling stations, each with 500 cars/d capability (2.7 tonnes/d H_2); a home option for one car is also examined. Three main options, and some subdivisions, are costed.

The options and costs under today's market conditions, are:

1. Large-scale LH_2 production at remote natural gas wells, by steam methane reforming (SMR), shipped by tankers an average of 800 km to 10-100 fueling stations. The remote plant maintains 5 days storage, the fueling station 1.5 days' storage, and the LH_2 is vaporized at 340 atm for vehicle use. The H_2 price at the station would be \$3.35/kg for a 27 tonne/d remote plant, and \$2.35/kg for a 270 tonne/d plant.
2. Large regional and local GH_2 production by SMR of natural gas at 15-30 atm.; 50-km pipelines in straight radial directions, each with 10 fueling stations spaced 5 km apart. Only 1.5 days' storage at plant, none at fueling stations. The H_2 price at the station would be \$2.91/kg for 27 tonnes/d plant feeding one pipeline, and \$2.47/kg for 270 tonnes/d plant feeding 10 pipelines.
3. Individual fueling station producing 2.7 tonnes/d H_2 by SMR of natural gas. One-half day storage at station. The H_2 price would be \$3.57/kg.
4. Same as #3, but using on-site partial oxidation of heavy oil as production method. The H_2 price would be \$3.96/kg.
5. Home garage electrolysis producing 3 kg/d GH_2 for one car, half tank per day. The H_2 price would be \$6.97/kg.
6. Same as #3 and #4, except methanol stored and reformed at fueling station. The H_2 price would be \$3.76/kg.

The paper concludes with a discussion on how the market could grow, depending on the preferred form of on-board hydrogen storage.

Specht, M., et al., "Comparison of the renewable transportation fuels liquid hydrogen and methanol with gasoline--energetic and economic aspects," Center for Solar Energy and Hydrogen Research, University of Stuttgart, Germany, pp. 227-239**.**

These researchers have developed a process to extract CO_2 from the atmosphere and combine it with H_2 from sources such as hydroelectricity to produce methanol. This process, which includes shipping the product to Europe, is now compared to LH_2 from the same hydropower, and both are compared to crude oil-gasoline production from energy efficiency and cost viewpoints.

The overall efficiency of the crude oil-gasoline-vehicle system is about 19%, compared to about 9% for LH_2 and slightly more for pure methanol. The costs are determined largely by the energy input and capital cost of production plants. When used in ICE cars, the renewable-based methanol and LH_2 are approximately equal; gasoline is about 25% cheaper, all based on untaxed fuel.

Apart from a possible tax advantage for environmentally benign fuels such as LH_2 and methanol, the advent of commercial FCs would swing the balance away from gasoline. Considering infrastructure and vehicle components, methanol shows a considerable advantage over LH_2.

Provenzano, J., et al., "Demonstration of fleet trucks fueled with PV hydrogen," Clean Air Now, California, USA, pp. 283-291.

The authors describe the initial results with three trucks, after illustrating details of the integrated photovoltaic generation of H_2 and storage facilities.

Despite some misfiring, performance is satisfactory, with substantially more power than on gasoline, and of course very low emissions: <100 ppm NO_x at maximum power, <0.1 g/mi total ($CO+HC+NO_x$), down from 0.37 g/mi of the first prototype (which is presumably the Item 10 Table 1).

[Topic 2, technologies of hydrogen production, id not contain papers relevant to this discussion.]

TOPIC 3: <u>Technologies of Hydrogen Storage and Transport</u>

Lund, P., "Improved Possibilities in Energy Storage through Hydrogen Technology," Helsinki University of Technology, Finland, pp. 981-992.

At present, the most promising approaches to small- and medium-scale energy storage are H_2-based: Ni-metal hydride batteries, and H_2-FC stand-alone systems.

A practical electric vehicle would thus be based on H_2 energy, with metal hydride as anode and Ni as cathode, and perhaps even a solid electrolyte. In comparison with Ni-Cd (40-50 Wh/kg), and even worse Pb-acid (30–40 Wh/kg), the Ni-MH battery ranges from 50 to 90 Wh/kg depending on the hydride used, and has potentially longer lifetime and flexible electrode design.

The author stresses the fact that the huge increase in demand for rechargeable batteries during the past decade for consumer electronics has led to the development of Ni-MH batteries substituting Ni-Cd, mostly for environmental reasons. The price-capacity ratio is about the same, but the Ni-MH variety has the potential to decrease by a factor of 2.0-2.5. EV-scale Ni-MH batteries are being developed in Japan by Toyota (110 Ah) and by Panasonic (130 Ah) with energy density of 70-80 Wh/kg and power density of 170 W/kg.

In future the Ni electrode could be replaced by air, giving a higher energy density of 90–100 Wh/kg, and perhaps much more.

Ewald, R., "Requirements for Advanced Mobile Storage Systems," Messer Griesheim, Krefeld, Germany, pp. 1029-1042.

This paper gives a review of on-board storage methods, especially for cars and buses, and emphasizes that a successful hydrogen vehicle must be tailored to the hydrogen fuel and its form of storage.

Although liquid or slush H_2 is the only feasible form for aviation, it is still too early to chose between GH_2, MH, and LH_2 for ground vehicles, because the vehicle application parameters and the fuel availability/price have significant influence. He offers the following state-of-the-art comments:

- For GH_2, there's no point in going >300 bar, because of difficult infrastructure and decreased filling factor from non-ideal gas behavior

- Cryogenic GH_2 is still in the R&D phase, and needs thermal management
- Micro-sphere GH_2 is still in laboratory phase
- LH_2 is good but expensive
- Slush (half solid, half liquid) has 15% higher density than LH_2, but is too difficult
- MH is safe, but needs thermal management, and impurities are problematic
- Organic liquid hydrides (methanol, LNG, MCH) are good if direct use is feasible.

Yamane, K.; S. Furuhama, "A Study on the Effect of the Total Weight of Fuel and Fuel Tank on the Driving Performance of Cars," Musashi Institute of Technology, Tokyo, Japan, pp. 1053-1062.

Using simplified equations, a parameter study was performed to find the influence of total weight of fuel and fuel tank on fuel economy, range, starting and running accelerations, maximum grade, and maximum vehichle speed.

The influence is quite strong, and as far as the various hydrogen options (300 bar GH_2, MH, LH_2) and a battery EVs are concerned, LH_2 is much superior for driving range and fuel economy. They concluded that to satisfy the necessary conditions, and therefore an acceptable weight of fuel and fuel tank, only LH_2 provides a practical solution.

Michel, F., et al., "Onboard Equipment for Liquid Hydrogen Vehicles," Messer Griesheim, Cologne, Germany, pp. 1063-1077.

This paper shows how on-board LH_2 storage tanks have improved during the past 20 years: doubling of energy density, and nine times less evaporation rate; in fact, today, no evaporation losses need occur for several days.

The authors also report on the improvements of several detailed components that influence the safety and the fuel supply.

The safety tests were done together with BMW (see Pehr [1996]).

An example of new components is a device for pressure control of LH_2/GH_2 fed to the engine: a special metal hydride in the insulation space of the cryotank. By varying the heating to the hydride, more or less gas is formed, changing the heat transfer and therefore the pressure in the inner tank.

Another device maintains a constant low temperature of the cold GH_2 to the engine; if this temperature is too high an ICE suffers power loss; if too low the heat source (engine cooling water) can freeze.

Ogden, J.M., "Development of Infrastructure for Refueling Hydrogen Engines," Princeton University, New Jersey, USA, pp. 1113-1122.

If mandated levels are imposed, the Los Angeles basin will have several 10^5 ZEVs by 2010.

This paper assesses the economics of various near-term possibilities for producing and providing GH_2 for urban transport vehicles, and how a refueling infrastructure might evolve during the next few decades. Conceptual designs of refueling stations and delivery systems were established for each of five major options, in each case supplying 100–1000 cars or 200-300 buses/d for a total per station 0.1-2 million scf/d. The five options are:

1. NG/LH_2 ;	truck LH_2 ;	store/vaporize ;	fuel vehicle.
2. NG/GH_2 ;	pipe GH_2 ;	compress/store ;	fuel vehicle.
3. Refinery GH_2 ;	pipe GH_2 ;	compress/store ;	fuel vehicle.

4. NG local network; reform to GH_2 compress/store ; fuel vehicle.
5. Off-peak power ; electrolysis ; compress/store ; fuel vehicle.

No clear winner emerges from the analysis, but options 2 and 3 are the most, and 4 the least, interesting at the lower end of station capacity; at the higher end, a substantial cost convergence takes place.

The indicated strategy is to:

- Start fleets with trucked LH_2 or with on-site reforming or electrolysis
- Make small increments on a dispersed area with on-site reforming or electrolysis
- When several 10^4 vehicles involved, build a small, dedicated GH_2 pipeline from a refinery or other excess H_2 facility
- After $5.10^5/2.10^6$ vehicles are involved, build a new H_2 facility with a local pipeline
- For the long-term, as natural gas becomes too expensive, phase in renewable energies.

Wetzel, F.-J., "Handling of Liquid Hydrogen at Filling Stations," Solar-Wasserstoff-Bayern, Munich, Germany, pp. 1123-1134.

SWB is a joint venture between the local utility Bayernwerk, BMW, Linde, Siemens, and operates the industrial-scale solar hydrogen demonstration facility in southern Bavaria. Among the ongoing activities, this paper focuses on the progress made since 1991 in reducing the LH_2 losses and time for the last of the four major transfers: liquefier to storage tank; to transport tanker; to filling station; to vehicle tank. These losses are particularly severe with LH_2 because of the 30% liquefaction energy.

Two systems have been studied for fueling BMW cars from the 3,000-liter LH_2 tank at the facility to the 120-liter on-board tanks: by pressure head; and by LH_2 pump. Recent improvements in losses and filling times have come from better cryogenic fluid flow management, and from novel couplings.

There are essentially three phases in filling a car tank: connections and cool-down; filling proper by opening and closing the LH_2 valve; depressurize connecting lines, disconnect. All operations are automatic except for the simple ones of connect and disconnect.

The main results are:
- Total times for filling down to 8.6 or 5.2 min, depending on the coupling used
- Total LH_2 losses (largely recuperable) down to 14.2 or 8 liters, respectively.

On this basis the conclusion is that there are no longer any prohibitive restrictions on LH_2 handling in the distribution process, including vehicle filling. A new, optimized station layout was elaborated.

Hettinger, W., et al., "Refueling Equipment for Liquid Hydrogen Vehicles," Messer Griesheim, Cologne, Germany, pp. 1135-1143.

A combined road tanker (6,000-liter LH_2) and filling station has been developed for demonstration projects in which the firm is involved (see Tables 1 and 2). For this purpose, two separate approvals have been issued by the licensing authorities.

The paper describes the filling procedure, focusing on the clean-break coupling (one of those used in the Wetzel tests above) which, attached to two flexible hoses, make the connection to the vehicle. This connection can be broken, even during filling, without letting air or humidity inside the tube system.

Pizak, V. et al., "Investigations of the Kinetics and Catalysis of the Iron/Steam-Magnetitie/Hydrogen System in low temperature regime with regard of its use to produce and store hydrogen," Center for Solar Energy and Hydrogen Research, Ulm, Germany, pp. 1175-1183.

This poster presentation examines an old method for H_2 production—reacting steam with red-hot sponge iron-for suitability for on-board use, especially using sponge iron from the direct reduction of iron process.

After some fundamental work on the kinetics of the reaction, the main result seems to be that a very large and stabilized surface area of sponge iron is needed at temperatures lower than 300ºC. The method is, however, practicable for hydrogen generation from sponge iron (which in turn could have been produced by H_2 reduction of the ore), but best introduced in heavy transport systems such as locomotives or submarines.

TOPIC 4: <u>Technologies of Hydrogen Utilization</u>

Scott, D.S., et al., "Harvesting Thermomechanical Energy from LH_2: Transportation Applications," University of Victoria, British Columbia, Canada, pp. 1449-1452.

The authors point out that the 10% thermomechanical energy in LH_2 should not be wasted, concentrating only on its 90% chemical energy. By comparison, gasoline has 0% thermomechanical energy and steam has 100%.

An example of how to harness this 10% in LH_2 would be to use it as the heat sink in a cryogenic heat engine. There are other possibilities that the designer should stay alert to.

Peschka, W., "Hydrogen the Future Cryofuel Fuel in Internal Combustion Engines," German Aerospace Research Establishment, Stuttgart, Germany, pp. 1453-1481.

This comprehensive review of the successive improvements in ICE performance with LH_2 fuel takes as a starting point the order-of-magnitude advantage that the ICE has over the FC for specific power (kW/kg), with today's technology or even with advanced technology.

After reviewing the problems with external mixture formation, and internal mixture formation with early-start injection, he concludes that latter not much better than former, and that late-start injection (~ 5º BTDC), although it resolves most problems, has only about 5 ms at 5,000 rpm for injection, mixing, ignition, and combustion. This means that 15–20 Mpa LH_2 injectors are needed to inject much increased gaseous fuel volumes (in small and medium vehicles, cryogenic H_2 is always gas in combustion chamber) in the 2-3 ms available.

He therefore feels that the optimum solution is a hybrid one: early-start injection of 0.4-0.5 Mpa LH_2 into a lean mix, ignition at ~5º BTDC with no pre-ignition or NO_x; then cryogenic H_2 injected at 20 MPa into flame front at ~5º BTDC giving turbulence and mixing. This hybrid allows very low NO_x, and gives similar engine performance (power and torque) as conventional fuels.

He claims that fuel conditioning systems for LH_2/ICE is much cheaper than low-cost FC.

Naber, J.D.; D.L. Siebers, "Hydrogen Combustion under Diesel Engine Conditions," Sandia National Laboratories, California, USA, pp. 1503-1512.

There are potential advantages in efficiency, power density, and safety in hydrogen engines running under diesel direct-injection conditions, compared to premixed, spark-ignited conditions.

The experiments simulated constant-volume diesel conditions by combusting lean, pre-mixed gas with hydrogen injection when the mixture cools to diesel conditions. Exhaust gas recirculation, as a means of lowering NO_x, was also studied.

The results showed that a late-cycle, direct injection H_2 engine can meet ULEV emission standards for NO_x without exhaust gas after-treatment, by using intake charge dilution techniques. TDC temperatures can be increased and O_2 concentration decreased simultaneously through high levels of exhaust gas recirculation.

Digeser, S., et al., "The Intercooled Hydrogen Truck Engine with Early Internal Fuel Injection--a means of achieving low emissions and high specific power output," Daimler-Benz, Stuttgart, Germany, pp. 1537-1546.

This report presents the state of development of the H_2 engine with early internal fuel injection, as previously foreseen for Item 2 Table 1.

After ruling out external mixture formation because of well-known backfiring, pre-ignition, and knock contributing to low power-to-size ratio, early internal mixture formation is chosen to give enough time for charge mixing, especially with lean-mix operation as required for low NO_x.

Exhaust gas turbocharging is particularly suited to H_2 engines because of the higher exhaust enthalpy resulting from high water vapor content and higher temperatures, and combats the power disadvantage of lean mixtures. Under these conditions, an H_2 pressure of 40 bar can inject fuel even at full load.

The report gives further details of this engine development.

Kondo, T., et al., "A study in the Mechanism of Backfire in External Mixture Formation Hydrogen Engines," Musashi Institute of Technology, Tokyo, Japan, pp. 1547-1556.

Backfire in external mixture formation H_2 engines occurs when the excess air ratio is 2 to 3. Several theories have been proposed to explain backfire: a nuclear theory of ignition; temperature rise in spark plug; combustion products remaining in top piston land. None, however, has led to complete elimination of backfire.

This study shows that one cause can be discharge of the electric energy remaining in the spark plug cable after ignition, and when the pressure in the cylinder becomes low enough on the inlet stroke.

In fact, in H_2 engines the H_2-O_2 flame has a lower ion concentration, and thus a higher resistance, than that of a gasoline engine; some undischarged residual electric energy therefore remains in the floating capacity of the cable connection between the ignition coil and the spark plug, and can be discharged when the low-pressure conditions of the inlet stroke permit.

The tests in a special test engine showed that if the residual electric energy is discharged quickly after ignition through a special resistor to earth, no backfire from this cause occurs down to stoichiometric air/fuel ratio, and low engine speed.

Valdimarsson, P.; B. Arnason, "Design of a Pre-chamber for IC Engines operating on low-pressure hydrogen," University of Iceland, Reykjavik, pp. 1569-1578.

Tests were conducted to examine how low-pressure H_2 from abundant hydropower via electrolysis could be used to fuel the fishing fleet, which consumes almost 44% of the total transportation fuel energy in Iceland, by easy retrofit of engines.

Initial tests on a representative engine (150 kW, six cylinders, natural gas) were performed with GH_2 at 2-20 bar and 300–400º C from magnesium hydride storage; the external mixture formation led to violent backfiring.

Another approach consisted of a pre-chamber fitted to the combustion chamber whose volume was decreased accordingly; low-pressure 2–20 bar GH_2 was injected into the pre-chamber in the latter part of the inlet stroke and first few degrees of the compression stroke; some H_2 entered the main cylinder giving a lean mixture, and was forced back into the pre-chamber where the rich homogeneous mixture was spark-ignited.
Good results in terms of no backfiring were obtained, and decreased throttle response was traced to excessive throttling in the passage connecting the pre-chamber to the main cylinder. Further engine-specific modifications are required.

Meier, F., et al., "A Study of Mixture Formation and Flame Speed in a Hydrogen Direct Injection SI Engine," University of Stuttgart, Germany, pp. 1587-1599.

In order to study instationary H_2 combustion in a direct-injection spark ignition engine, high-speed Schlieren experiments were performed in a single-cylinder transparent test engine representative of real engine conditions.

Although internal has great advantages over external mixture formation (no backfire, ~30% more power, no pre-ignition if late imf), little time is available for mixing. So multi-dimensional techniques are needed to investigate mixture formation before ignition. Therefore, a quantitative technique was developed, giving high temporal and two-dimensional spatial resolution, based on Raman scattering of H_2 molecules; flame speed after ignition was measured by Schlieren photography.

Good results were obtained, at least as far as measuring techniques are concerned. Among the many results quoted, with imf the turbulent flame speed seems to be about six times that of propane; with emf this factor decreases to about three.
Brown, R.K.; R.K. Green, "An Investigation of a Hydrogen Fueled Wankel Engine," University of Canterbury, Christchurch, New Zealand, pp. 1601-1610.

Previous work by these authors on late direct injection of H_2 in reciprocating engines had shown the absence of backfire, pre-ignition, and auto-ignition. High-pressure H_2 injectors are however a problem, and leakage -both wasteful and dangerous- can occur with solid seating elements during the expansion and exhaust strokes (an elastomeric seat can eliminate the leakage but has poor durability).

The Wankel engine promises several advantages using H_2 emf:
- Physically separate inlet, combustion, exhaust processes
- No exhaust valves and corresponding hot spots
- Injector leakage always into compression stroke, thus solid seats acceptable
- Good for stratified charge in combustion chamber, thought to offer << NO_x.

A special-purpose single-rotor Wankel engine was equipped to run on 1.5 bar GH_2 injected to inlet manifold and controlled by upstream regulating valve. Measurements were made of combustion chamber pressure, crank angle, inlet and outlet temperatures of all fluids, fuel flow rates, exhaust gas composition.

Results confirmed absence of backfire, pre- and auto-ignition over a wide range of loads and air/fuel ratios, but much decreased maximum power and lower efficiency at full power, compared to gasoline. The NO_x emissions at part load (lambda >1.8) are negligible, increasing rapidly as stoichiometry (full load) is approached to considerably higher than with gasoline.

Work will continue on early and late direct injection to improve maximum power output.

Knorr, H., et al., "The MAN Hydrogen Propulsion System for City Buses," MAN Nürnberg, Linde Höllriegelskreuth, Germany, pp. 1611-1620.

This bus is that given as Item 3 Table 1, now in service on scheduled routes in Erlangen. The paper gives the initial performance data as reported in Table 1.

Dönitz, W., "Fuel Cells for Mobile Applications, status, requirements and future application potential," Daimler-Benz, Friedrichshafen, Germany, pp. 1623-1636.

This paper takes as starting point the recent enormous strides in the technology and power density of PEM FC, without minimizing the requirements for a new technology such as FC to compete with the highly developed ICE.

The attraction is the very dynamic worldwide car market. For example in Germany alone, the installed power of passenger cars is about 10 times the installed capacity of public power plants, and the rate of increase of the former is about twice that of the latter.

The PEM is taken as the only suitable FC for mobile applications, because its power density is significantly higher, and its low operating temperature means rapid on/off without major energy losses. The high cost of these cells is dominated by the Pt loading of the electrodes and the solid membrane used.

Pt loadings have decreased from 8 mg/cm^2 in 1990 to ~2.2 today with 0.3 as the long-term goal; in parallel the power density has increased from 0.5 in 1990 to 0.8 today with 1.0 as long-term goal. So, with Pt costing 20 DM/g, the electrode loading cost is down from 320 DM/kW in 1990 to ~55 today with 6 as long-term goal. So this cost item is very likely no bar to commercialization, and Pt recycling from used cells will help.

The membrane cost, at ~800 \$/m^2 (~250 DM/kW) for Nafion, is still far too high for commercialization. Increasing production volume, and new polymer chemicals under development in other countries, will bring it down.

The paper reports on the results with the van of Item 9 Table 1, fitted with a 1990 Ballard 50-kW PEM FC. The present FC volume of 1,800 liters can be reduced to 500 liters as an immediate step. By the first years of the next century the power density should approach that of the ICE at <1 kg/kW.

The author sees methanol allowing easier introduction and market penetration for FC, but compact reformers must be developed.

Cleghorn, S., et al., "PEM Fuel Cells for Transportation and Stationary Power Generation Applications," Los Alamos N.L., New Mexico, USA, pp. 1637-1646.

This paper describes LANL's efforts to develop a low cost/high performance hydrogen or reformate air stack, based on ultra-low Pt loadings and on non-machined inexpensive elements for flow fields and bi-polar plates. On-board methanol reforming is compared to direct methanol FCs in light of significant power density increases of the latter.

The achievements so far are:

- Thin-film catalyst layer application gives ultra-low Pt loadings of 0.2 g/kW, which in 5,000-h tests produced 6 kW/m^2 using pressurized H_2/air
- Off-the-shelf stainless steel screens as flow fields, in place of the expensive machined metal ones normally used, showed relatively good performance;
- A significant increase in CO tolerance at anode to >>100 ppm with reformed hydrocarbon
- The record high performance of polymer electrolyte direct methanol FCs with Nafion as hot as 130ºC, already achieved by Siemens, has been repeated, and the future of this FC is promising provided that catalyst loadings can be further reduced or changed, long-term stable performance is demonstrated, and that methanol cross-over to the cathode can be minimized to acceptable levels.

The authors feel that commercialization is likely to occur for stationary applications first, because of less stringent requirements on overall cost, space, and nature/source of the H_2 fuel; the PEM FC, even in relatively small sizes by comparison with molten carbonate or solid oxide FCs, could be attractive in some applications such as peak power, demand-side management, and dispersed power generation.

Mantegazza, C.; A. Maggiore, "PEFC Activities at DNP," De Nora, Milan, Italy, pp. 1647-1656.

This paper is a review of the work since 1990 developing 5- and 10-kW PEM FCs, especially for the bus of Item 6 Table 1 and the car of Item 9 Table 2.

The present approach is to develop a metallic material for the stack structure with good crash resistance, low-cost production potential, corrosion resistance, commercial availability, and recyclability, compared to the precise and delicate materials used so far.

The first 5-kW unit had low power density of 40 W/kg, easily improved to about double by going to low-voltage, high-current stack design; so far >6000 h in 40 units of various sizes have been accumulated.

A small (0.5-kW) unit with reformed methanol containing 500 ppm CO has also been successfully demonstrated.

The 10-kW prototype for Item 9 Table 2 was tested in January 1996 at 100 W/kg.

By 1999, a 250-W/kg unit is foreseen, and stack selling prices should drop to $600/kW, opening commercial possibilities, at least in the stationary field.

Barbir, F., "Control Strategy for a Vehicular Fuel Cell Power System," Energy Partners, Florida, USA, pp. 1695-1705.

As part of the FC car development of this company (Item 13 Table 1), various control strategies have been simulated.

In vehicular applications, the FC system must supply power on demand in a highly variable load profile e.g. zero to full power in seconds. The FC itself has a response time of milliseconds; the H_2 supply is passive by static pressure; but the oxidant (usually air) must flow through the stack to remove the inerts (usually nitrogen) and product water. Although high air pressure and flow are beneficial to FC performance, the compressor power reduces overall performance.

Three air control strategies were simulated: constant pressure and flow; constant pressure and variable flow; and variable pressure and flow.

The first strategy is the simplest, and was adopted for the car of Item 13 Table 1, but gives considerably lower efficiency especially at low loads (the fuel consumption is at least doubled up to 12.5% load) compared to the other two strategies, which are essentially equivalent. From 50% load up, all three strategies have similar fuel consumptions, the slightly better one of the third strategy being compensated by the disadvantage of special compressor development specific to this application.

The second strategy is therefore the most indicated one, giving an overall efficiency higher than 37% at full load compared to about 22% for the first one.

Wurster, R., et al., "Feasibility Study on Fuel Cell Propulsion for Urban City Buses and Delivery Trucks," LBST, Neoplan, MAN, Magnet-Motor, Daimler-Benz, Siemens, ESTW, Linde, SWB, all in Bavaria, Germany, pp. 1707-1716.

Two PEM FC buses are apparently now decided on the basis of the feasibility study and concepts reported here. Hardware procurement started early 1996. Two buses--one each from Neoplan and MAN--should be ready by early 1999; a delivery van from MAN may be decided at a later date. The city of Erlangen in Bavaria, where the MAN bus of Item 3 Table 1 is now in regular operation, is a probable choice for the demonstration. The state government of Bavaria and the federal government of Bonn have been asked to co-finance 50% of the entire activity.

The costs of the project (including the two demonstration buses, the peripheral equipment, and a 6-month test phase) will be about 20 million DM, the most costly component being the fuel cell system.

A selected summary of the most important characteristics follows:

1. The MAN bus will have a 120-180-kW PEM-FC powering a central drive motor.
2. The Neoplan bus will have a 60-90-kW Siemens PEM FC in hybrid combination with magneto-dynamic flywheel of Magnet-Motor (2 kWh, 150 kW short-term average), powering two wheel-mounted drive motors.
3. Both buses will have a passenger capacity of 100 persons, a length of 12 m, a total weight of 18 tonnes, and low floor layout (100% in the Neoplan case because of wheel-mounted drive motors).
4. GH_2 at 25 MPa in 12 fully composite roof-top cylinders (total 2.2 m^3) gives each bus a range of 120-300 km/d with daily refueling.
5. The FC module in each case is expected to have an overall net efficiency (based on the lhv of H_2) of ~55% at full power, and a maximum of ~63% at ~20% power. Air will be supplied at 0.15 MPa.

Schmidt, V.M.; U. Stimming, "Hydrogen and Methanol Proton Exchange Membrane Fuel Cells," Forschungszentrum Jülich, Germany, pp. 1717-1725.

This paper presents concept studies, as well as test results, on CO-tolerant catalysts.

The PEM and A FCs are the only ones for relatively low-temperature operation (60º-100ºC), so good for vehicles (as well as stationary) applications. The PEM FC has the additional advantages of low voltage degradation, good long-term stability, high power density, and favorable overload behavior. Besides, its lack of a corrosive liquid electrolyte gives an edge in safety and compactness; and it is fuel- and reactant-tolerant; i.e., it can accept, up to a point, CO contamination (even methanol) at the anode, and air at the cathode; in contrast, the A FC needs pure H_2 and O_2.

Laboratory tests were carried out with pure H_2, and H_2 with 100 ppm CO as fuel; and with pure Pt, $Pt_{0.5}Ru_{0.5}$, and $Pt_{0.7}Ru_{0.3}$ as anode catalyst. The main results were:

- Maximum power density with $Pt_{0.5}Ru_{0.5}$ higher than with pure Pt by a factor of 4
- No significant difference in power density for pure H_2 or for H_2/100 ppm CO up to 0.4 A/cm^2 current density.

The paper discusses some concepts for direct methanol PEM FC.

Scherer, G.G., et al., "Materials Research Aspects of Membrane Development for Polymer Electrolyte Fuel Cells," Paul Scherrer Institut, Villigen, Switzerland, pp. 1727-1736.

In this work, the preparation of novel proton conducting membranes is described.

A three-step process is involved: first, the base polymer is irradiated by a gamma or electron source to create radicals as reactive sites; second, a monomer or monomer/crosslinker mixture is grafted onto the activated polymer; third, the grafted film is sulfonated.

Initial characterization tests are described in this complex materials problem.

Friedrich, J.; K.E. Noreikat, "State of the Art and Development Trends for Fuel Cell Vehicles," Daimler-Benz, Stuttgart, Germany, pp. 1757-1766.

This paper starts with some important vehicle statistics and projections, and takes the FC car as one of the most interesting alternative drive concepts to meet future needs and satisfy environmental requirements.

The present worldwide vehicle population amounts to some 500 million cars and 170 million commercial vehicles. With an annual increase of 17 million, the total becomes 1.6 billion in 2030. The total traffic-related CO_2 emissions on this basis goes from 4.4 billion tons in 1995 to 6.7 billion tons in 2030 (their Figure 1 gives the breakdown by four categories of vehicle, and separately by six regional blocs).
The ICE and FC physically separate the energy converter from the energy storage; batteries do not.

Vehicle drive systems should possess four equally important properties, interlinked and sensitive to one another: efficiency; power; transient response; range.

The ICE has an efficiency drawback, but will probably dominate for the foreseeable future. A new drive system that can use the distribution system of conventional hydrocarbon fuels starts with an enormous advantage, so FC with methanol may be a natural successor.

After examining 10 advantages of FC, and discussing the types of FC, the conclusions are reached that the PEM FC with H_2 fuel is most indicated for city buses and public service vehicles making use of centralized fueling and maintenance; the PEM FC with methanol reforming is most indicated for vans, minivans, and private cars.

The Mercedes van of Item 9 Table 1 has been in operation for about 2 years, and is the fruit of a strategic alliance with Ballard. The 20-kg/kW FC without buffer energy storage allows only modest acceleration, but improved FC will decrease this to 4-5 kg/kW in the future.

The customer requirements for drive systems are discussed, and mention is made of apparently trivial problems such as keeping the polymer membrane moist over the temperature range of -30º to +60ºC.

Finally Daimler-Benz estimates of cost trends for PEM FCs are presented as functions of innovation and production scale. From about the year 2000, a steep rise in quantity and somewhat less steep drop in cost per kW is expected over about 5 years, dropping off thereafter. The present cost of 80-100,000 DM/kW for demonstration units should drop to 600-700 DM/kW by 2010.

Studies commissioned by GM and Siemens conclude that FC drives can be manufactured in high unit numbers for 100-110 or 300-500 DM/kW, figures Daimler-Benz still finds very optimistic.

In conclusion, the fuel infrastructure costs and production engineering are regarded as critically important to the FC future, whereas the core technical problems of the FC unit and peripherals can probably be solved with relatively little difficulty.

Bevers, D., et al., "Innovative Production Procedure for Low Cost PEFC electrodes and membrane structures," DLR, Stuttgart, Germany, pp. 1767-1776.

A need is identified for mass production of reproducible PEM FC electrodes by a rolling technique well known for alkaline battery electrodes.

This rolling process was developed with the required potential, and future improvement steps are outlined.

TOPIC 5: Materials and Safety

Linney, R.E.; J.G. Hansel, "Safety Considerations in the Design of Hydrogen-Powered Vehicles," Air Products and Chemicals, Pennsylvania, USA, pp. 2159-2168.

Pointing out that on-board hydrogen will bring the public closer to it than any prior application, that the public is risk-intolerant, and that there are no generally accepted design regulations that cover all aspects of such use, this paper examines:

- Design considerations focusing on safety
- Flammable mixtures surrounding leaks
- Venting hydrogen from vehicles.

And some real-life situations that could arise.

Quantified risk assessment with the fault tree technique could then lead to an evaluation of the risk to vehicle occupants and nearby public.

One important result from this paper is that in many real leak scenarios, high release velocities of the H_2 and normal ambient winds overshadow the buoyancy/diffusivity advantages, so that 5,000 psig H_2 leak can reach further horizontally than 3,000 psig CH_4.

Pehr, K., "Experimental Examinations on the Worst Case Behavior of LH_2/LNG Tanks for Passenger Cars," BMW, Munich, Germany, pp. 2169-2186.

To ease the introduction of a new technology, examining some of the worst-case accidents may be advisable, and would help overcome a subjective public assessment.

The worst case for LH_2/LNG tanks is a burst releasing all mechanical, chemical, and thermal energy stored. An experimental series of tests was divided in two parts to test the consequences:

1. LH_2 was abruptly released at 2.5 times the operating pressure using a cutting charge. This gave information on the fundamental processes involved when LH_2 tanks burst, an obvious conclusion being that the operating pressure should be kept as low as possible.
2. A fault tree analysis identified the potential real mechanisms for burst (pressure buildup, fire, mechanical damage), and the consequences were measured.

The pressure buildup tests, such as could happen in a severe road accident, were simulated by destroying the vacuum insulation and blocking the overflow/safety valves. The buildup gives an initial crack which at critical length or growth rate can give catastrophic rupture, or which can give leak-before-break. With the minimum regulatory wall thickness (2 mm) the pressure reached bursting value in 10 min, which was 15 times the maximum permissible one. The effects of these tests have been already described in Pehr (1994, 1995). With a 50% thinner wall, the initial crack allowed leak-before-break, effectively avoiding rupture.

The fire tests were made with ignited propane giving >900ºC temperatures over and near the tank surface; the heat flow inward, heating and evaporating the hydrogen, was as high as 27 kW. The test rig meets the IAEA requirements for fire tests.

Two tanks were subjected to the fire tests: one with inner and outer vessels of austenitic stainless steel, the other with outer vessel of the same steel but the inner vessel of cold-tough aluminum alloy. The safety valves were placed outside the fire zone to prevent premature leak, but the unburned hydrogen was <10% of the propane flow.

With the inner Al alloy/outer SS combination, the safety valve was fully open after 4 min, the LH_2 was completely gone after 10 more min, at which point the inner vessel started to melt. With the SS/SS combination, no visible or measurable change occurred for another 60 min after evaporation of the LH_2, at which point the test was terminated.

Overall, the energy stored was released slowly and hardly noticeably in the fire tests, and the tank behavior was benign.

If the safety valves are left in the fire zone, they still open with their full cross-section.

In the external damage tests, two methods were employed: a blunt object dropped to give severe deformation, a pressure peak and rupture; a sharp object dropped to penetrate both walls.

In the blunt series, the pressure peaks reached 0.7 bar, small cracks in inner vessel gave leaks, loss of vacuum insulation, safety valve lift. If the outer vessel is also cracked, then the escaping H_2 can burn as long as 55 min.

In the sharp series, both tanks were penetrated, no crack propagation occurred, H_2 leaked from punched corners, burned initially as a cloud in ~1 sec, then slowly at tank for ~20 mins before auto-extinction.

Würsig, G.; U. Petersen, "Early Stage Safety Analyses for Hydrogen Process Systems," Germanischer Lloyd, Hamburg, Germany, pp. 2187-2201.

The aim of these studies was to examine at an early stage the technical feasibility of concepts, and to develop design requirements derived from safety considerations. The overall project examined included the facilities of large-scale LH_2 transportation (115,000 m^3 tanker with 40-MW H_2 power plant), storage (1,000 tonnes LH_2) and distribution, and use (10 MW FC; 150 LH_2 bus depot) in the port and city of Hamburg.

The safety analyses in question are HAZOPS-style, before the P&I drawings have progressed enough to justify a full-blown fault tree approach. Preliminary flow sheets and process/function descriptions are required to some minimum level to allow concrete assessments, and especially to reveal weak points relatively easy to correct early on. Experience and expert judgement are required, and outsiders should join the insiders in the analyses.

Although the paper concentrates on the 40-MW power plant, the results for the other three indicate that they can be constructed from a safety viewpoint in Hamburg, and that in general design improvements derived from purely safety considerations lead also to operational benefits in the form of higher reliability and availability.

TOPIC 6: Fundamentals

Giesenger, A., et al., "Zeolite Powders as Hydrogen Storage Materials: Measurements and Theoretical Modelling of Thermophysical Properties," University of Stuttgart, Germany, pp. 2513-2522.

Zeolites are highly porous crystalline aluminosilicates, whose crystal structure with pores and cages enables the reversible encapsulation of guest molecules. Present uses are as molecular sieves and drying mediums, and recently for H_2 storage where the H_2 molecules are forced into the zeolite cages at 30 bar and 600 K. Reheating the loaded zeolite releases the H_2. The effective thermal conductivity of the zeolite powder strongly influences the velocity of adsorbing and desorbing hydrogen. The specific heat is a measure of the zeolite water content whose presence inhibits H_2 uptake.

The paper describes measurements of the thermal conductivity and specific heat, and their comparison with theoretical models. The application of the measurement techniques to synthetic zeolites with better H_2 storage capability is mentioned.

Fischer, A., et al., "Comparing different production technologies for Proton-Exchange-Membrane Fuel Cells," Technische Hochschule Darmstadt, Germany, pp. 2523-2530.

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It deals with the influence of the production technology on electrode porosity and FC performance, and shows the importance of coarse pores for thin film electrodes.

With H_2 at the anode, the catalysts cannot tolerate more than 10 ppm CO; with air instead of O_2 at the cathode the N accumulation there creates a barrier for O_2, so the electrode porosity is important to performance. To show this experimentally, the membrane/electrode assemblies were produced either by hot pressing platinized carbon percolated with Nafion as electrode material on Nafion 117 membranes, or by spraying an electrocatalyst slurry on to the heated membrane with subsequent drying; an additional porosity was implemented by adding fillers to the electrocatalyst slurry.